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Examining a Science Teacher's Pedagogical Content Knowledge: Interactions among Components through an Alternative Mapping Approach

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Abstract

This study investigates the interaction of a science teacher's pedagogical content knowledge (PCK) components during the instruction of seventh-grade physics topics—work/energy and simple machines. It aims to explore how these components interconnect and influence instructional practices, particularly in the context of teaching gifted students. The study employed a qualitative research design, using classroom observations as the primary data source. It utilized the Alternative Mapping Approach (AMA), an adaptation of Park and Chen's (2012) mapping-out method, to analyze PCK interactions. Content analysis and the constant comparative method were applied to interpret the data and construct detailed PCK interaction maps. The study yielded four key findings. First, PCK interaction maps are topic-specific and differ in complexity and structure. Second, student-related factors—such as learning difficulties, misconceptions, and characteristics of gifted learners—significantly influenced pedagogical decisions. Third, the teacher's knowledge of instructional strategies played a central role in initiating interactions, while knowledge of learners was crucial in addressing instructional challenges. Lastly, contextual factors, particularly the needs of gifted students, required enrichment activities that demonstrated dynamic interactions between knowledge of curriculum and other PCK components. This study contributes to PCK research by introducing the Alternative Mapping Approach (AMA) as a novel and effective tool for capturing the complexity and sequence of PCK component interactions. It highlights the importance of considering contextual and qualitative dimensions in understanding how PCK is enacted in real classroom settings, particularly in differentiated instruction for gifted learners.

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Introduction

Pedagogical Content Knowledge (PCK) refers to teachers' expertise in designing and implementing effective instruction tailored for specific student groups and contexts (Gess-Newsome, 2015; Magnusson et al., 1999; Shulman, 1986). Initially proposed by Shulman (1986), PCK goes beyond mere subject matter knowledge by emphasizing how best to deliver content to students. Recent studies highlight the critical role of PCK in enhancing teacher education and instructional quality, providing evidence-based approaches to improve teaching practices (Santibáñez et al., 2025). Strong PCK among teachers significantly contributes to improved student outcomes (Wilson et al., 2019).

Building on this foundational understanding, a growing body of research has explored the development and application of PCK across various science disciplines. In physics education, for example, studies have examined topics such as electrostatic force and electric fields (Mazibe et al., 2023) and force and motion (Azam, 2020). In chemistry education, examples include research on electrochemistry (Oztay & Boz, 2022), solubility (Boz & Belge-Can, 2020), and lactic acid (Barendsen & Henze, 2019). Similarly, in biology education, studies have addressed areas such as evolution (Khoza, 2024) and biodiversity (Ottogalli & Bermudez, 2024). Furthermore, contributions in science and engineering education have advanced PCK through Lesson Study initiatives (Lertdechapat & Faikhamta, 2025) and through investigations conducted within higher education contexts (Sarkar et al., 2024). While these studies offer valuable insights, the need for broader thematic diversity remains evident, underscoring the importance of continued interdisciplinary research to enhance the scope and impact of teacher education.

While science teachers' PCK is extensively studied, significant gaps remain regarding its classroom implementation. For instance, evidence connecting PCK directly to student outcomes is limited (Chan & Hume, 2019), and few studies explore how PCK specifically shapes teachers' classroom actions (Barendsen & Henze, 2019). Thus, future research should emphasize teacher-student interactions (Carlson & Daehler, 2019) and examine how teachers address student ideas during instruction (Wilson et al., 2019). Additionally, exploring how cultural backgrounds, learning levels, and individual differences influence teaching practices could offer valuable insights (Alkış Küçükaydın, 2019; Sarkar et al., 2024). The enacted PCK teaching cycle—comprising planning, teaching, and reflection—also warrants further investigation across diverse science topics. Because PCK is inherently topic-specific (Azam, 2020; Buma & Nyamupangedengu, 2023), additional studies can reveal strengths and weaknesses in teaching particular scientific concepts (Mazibe et al., 2023). Despite extensive research, inconsistencies in PCK conceptualization persist, emphasizing the need for standardized approaches (Sarkar et al., 2024). Moreover, while research often focuses on instructional decision-making, the interactive classroom phase remains understudied (Chan & Hume, 2019). Addressing these gaps could clarify how the teaching cycle impacts student learning outcomes (Wilson et al., 2019).

An often-overlooked aspect of PCK is the interaction among its components. Many researchers emphasize the need to explore these interactions further (e.g., Buma & Nyamupangedengu, 2023; Hlaela & Jita, 2024; Magnusson et al., 1999; Park & Chen, 2012; Park & Suh, 2019; Sæleset & Friedrichsen, 2021). However, comprehensive studies covering all components are limited (Galimova et al., 2023), and clear methods for examining their integration within teaching remain underdeveloped (Chan, 2022). To fill this gap, Park and Chan's (2012) Mapping-out approach illustrates interactions among PCK components, providing a valuable analytical tool for teacher educators and contributing to teacher education program design (Ottogalli & Bermudez, 2024). Although this approach clarifies enacted PCK cycles, it has limitations. It treats interactions between components as uniformly strong, preventing differentiation in their quality (Aydın & Boz, 2013; Şen, 2023), and overlooks their directionality and complexity (Şen, 2023). Moreover, it inadequately addresses contextual factors, such as student outcomes, which significantly influence teachers' PCK. To overcome these issues, Park & Suh (2019) proposed adjustments to mapping procedures and visual representations to better integrate these contextual influences.

Considering these limitations, this study aims to examine the interactions among a science teacher's PCK components while teaching the physics topics of work/energy and simple machines. The research question guiding this study is: *How do a science teacher's PCK components interplay when teaching work/energy and simple machines?*

Although recent PCK research in physics education has increased, it remains limited compared to chemistry, biology, and technology education (Melo et al., 2020). CoRe-based PCK studies predominantly focus on biology and chemistry, with few addressing physics teachers' PCK during CoRe construction (Aydeniz & Gürçay, 2018). A national meta-synthesis of 35 PCK studies from 2015-2021 identified only one physics-related study (Yolcu et al., 2022). Moreover, physics teachers typically demonstrate low levels of PCK, particularly in content knowledge. Although their pedagogical and curriculum knowledge is moderate, their knowledge of students and content remains limited (Hlaela & Jita, 2024). Considering these gaps, this research emphasizes the need to investigate physics-related PCK, providing insights into teachers' competencies and identifying areas for improvement (Mazibe et al., 2023).

Designed to explore enacted PCK in actual classroom settings, this study offers valuable implications for teacher education programs and ongoing professional development. Its key contributions include: (1) addressing prior limitations informed by Park and Suh (2019) through an alternative mapping approach (AMA), enabling comprehensive analysis of the teacher's PCK throughout the lesson; (2) revealing classroom interactions related to PCK components using AMA; and (3) examining a unique learning context involving gifted students. Gifted learners possess distinct advantages, such as rapid learning (Gilson, 2009; Reis-Jorge et al., 2021), high motivation (Renzulli & Reis, 2018), and complex questioning tendencies (Çaylak & Çakıroğlu, 2024) influence the teacher's use of PCK and its components, shaping these components accordingly (Çaylak & Çakıroğlu, 2024). Understanding how these student characteristics influence teachers' enacted PCK can significantly advance science education research.

The Framework of This Study

PCK, introduced by Shulman (1986), has been widely utilized as a theoretical framework to support science teachers' professional growth across diverse contexts, methods, and purposes (Carlson & Daehler, 2019; Loughran et al., 2006; Magnusson et al., 1999; Park & Oliver, 2008). To address variations and provide a universally adaptable framework, the Refined Consensus Model (RCM) was recently developed. RCM integrates elements from prior models, notably those by Shulman (1986) and Magnusson et al. (1999) (Carlson & Daehler, 2019). This study adopted the RCM to align with the established terminology in PCK literature (see Carlson & Daehler, 2019 for details), focusing specifically on enacted PCK (ePCK), the model's core component. ePCK refers to teachers' knowledge and skills (Gess-Newsome, 2015) and includes the processes of planning, teaching, and reflecting on specific science instruction. As defined by Carlson and Daehler (2019):

> This ePCK is the specific knowledge and skills utilised by an individual teacher in a particular setting, with a particular student, or group of students, with a goal for those students to learn a particular concept, collection of concepts, or a particular aspect of the discipline. (p. 83)

Additionally, Gess-Newsome (2015) described ePCK as: "Personal PCK&S is the *act of teaching* a particular *topic* in a particular *way* for a particular *purpose* to particular *students* for enhanced *student outcomes*" (p. 36). During the development of this component, teachers participate in a pedagogical cycle of planning, teaching, and reflecting. This cycle strengthens teachers' ePCK by enabling repeated refinement of their teaching of specific topics. Improvements result from two reflection processes: (1) reflection-in-action and (2) reflection-on-action (Park & Oliver, 2008), which shape future planning and enhance teachers' ability to clearly explain scientific concepts. Within ePCK, reflections are considered pedagogical reasoning (Carlson & Daehler, 2019). Additionally, student outcomes from teacher-student interactions significantly influence this pedagogical reasoning.

While the RCM provided the theoretical framework for this study, complementary models are necessary since PCK components are not fully visible within ePCK (Park & Suh, 2019). Additional models are needed to reveal teachers' practices and thinking during teaching (Carlson & Daehler, 2019), as RCM lacks tools to examine interactions among PCK components during instruction (Park & Suh, 2019). Thus, Magnusson et al.'s (1999) widely recognized PCK model was employed as a secondary framework (Chan & Hume, 2019). Magnusson et al. (1999) identified five PCK components:

1. Science Teaching Orientation (STO): Reflects science teachers' beliefs and knowledge about the goals and purposes of teaching specific topics.
2. Knowledge of Learners (KoL): Encompasses teachers' knowledge of their students, including the requirements for understanding specific concepts and difficulties, such as misconceptions or areas where students struggle.
3. Knowledge of Curriculum (KoC): Covers teachers' knowledge of goals, objectives, materials, and programs related to specific topics.
4. Knowledge of Instructional Strategies (KoIS): Includes both subject-specific strategies (e.g., inquiry, problem-based learning) and topic-specific strategies (e.g., simulations, analogies, or activities) used in teaching specific topics.
5. Knowledge of Assessment (KoA): Relates to teachers' understanding of science learning dimensions and assessment methods.

The Definition of Interaction in Teaching Science Topic

Interaction among PCK components refers to their reciprocal integration, where teachers simultaneously employ two or more components to initiate, sustain, or conclude planned instruction. For example, when introducing a concept, teachers may use a component to address alternative student conceptions, overcome difficulties, or offer hands-on activities (Park & Chen, 2012). Student outcomes from the KoL component might also prompt adjustments using other components, enabling cohesive management of unexpected or undesired situations (Magnusson et al., 1999).

One comprehensive study on PCK component interactions, conducted by Park and Chen (2012), introduced the "mapping-out approach." This tool clarifies how one component shapes others during teachers' instructional decisions. Employing the pentagon model (Park & Oliver, 2008), which assumes equal mutual relationships among components, they analyzed teaching episodes to create detailed PCK maps, facilitating comparisons of teaching practices.

Magnusson et al.'s (1999) model, however, prioritized STO, asserting that it influences other components. They emphasized interactions between STO and other components but did not address interactions between KoIS and KoC or KoL and KoA. Nonetheless, they stressed that cohesive interactions among all components are essential for effective science teaching and PCK development. Consequently, this study adopts the equal-interaction perspective proposed by Park and Oliver's (2008) pentagon model. Given increasing research into PCK component interactions, this study employs an alternative mapping approach (AMA) to further clarify how PCK components interact and how science lessons are constructed in practice.

Summary of Research on the Interaction among PCK Components

Understanding interactions among PCK components has become central in science education research, offering insights into how teachers integrate their knowledge to enhance student learning (Park & Chen, 2012). Early studies viewed PCK components as separate entities (Magnusson et al., 1999), but recent work emphasizes exploring their dynamic interactions in classrooms (Chan, 2022; Hlaela & Jita, 2024). Despite these advances, no standardized method exists for comprehensively analyzing these interactions (Chan, 2022). Park and Chen's (2012) pioneering mapping-out approach visualized connections between components, showing frequent interactions between knowledge of learners (KoL) and instructional strategies (KoIS), while knowledge of curriculum (KoC) was least integrated. They highlighted knowledge of assessment's (KoA) significant but overlooked role, particularly in informal evaluations. However, this approach was later criticized for treating interactions equally, neglecting their complexity and directionality (Aydın & Boz, 2013; Şen, 2023). Later studies refined this approach further. Aydın et al. (2015) showed mentoring improved preservice teachers' integration of components, especially KoC. Akın and Uzuntiryaki-Kondakci (2018) found experienced teachers integrated components more effectively than novices, emphasizing teaching expertise. Ottogalli and Bermudez (2024) revealed strong integrations between STO and KoL in biodiversity education, while KoA remained least integrated.

Research also highlighted variations in component integration based on experience and context. Demirdöğen et al. (2016) indicated preservice chemistry teachers primarily integrated KoIS and STO, with KoL underrepresented. Sickel and Friedrichsen (2018) noted early-career biology teachers initially prioritized curriculum and strategies, gradually incorporating student understanding and assessment. Similarly, Bayram-Jacobs et al. (2019) observed that while teachers often developed KoL and KoIS effectively, KoA was frequently underutilized, echoing previous findings (Akın & Uzuntiryaki-Kondakci, 2018; Barendsen & Henze, 2019). Additionally, Barendsen and Henze (2019) highlighted a mismatch between teachers' perceived PCK and actual classroom practices. Despite progress, two gaps remain: limited attention to physics education (Melo et al., 2020; Yolcu et al., 2022), and insufficient consideration of contextual factors, such as student characteristics, influencing PCK interactions (Çaylak & Çakıroğlu, 2024; Park & Suh, 2019). This study addresses these gaps by introducing the Alternative Mapping Approach (AMA), which integrates contextual factors and qualitative analysis into mapping. Unlike previous approaches, AMA recognizes differences in interaction strengths among PCK components, offering deeper insights into teachers' practices. By focusing specifically on physics topics (work/energy and simple machines), this study contributes to an underrepresented research area, providing a comprehensive understanding of how teachers dynamically integrate PCK components in authentic classroom settings.

Methodology

This study employed a basic qualitative research design with an interpretive approach (Creswell, 2007). To examine interactions among science teachers' PCK components, one science teacher was purposefully selected as the case, reflecting Shulman’s (1987) assertion that each teacher constitutes a unique case in PCK research. Case studies allow the exploration of contemporary phenomena within real-life contexts, particularly when boundaries between context and phenomenon are indistinct (Yin, 2009). Therefore, this case study holistically collected and analyzed data to reveal interactions among PCK components during authentic classroom teaching.

The participant was selected through purposive sampling to clearly define the case and maintain the study’s focus—an approach suitable for case studies (Fraenkel & Wallen, 2009; Merriam, 2009). The study utilized secondary analysis of previously collected data (Çaylak & Çakıroğlu, 2024). Due to the initial study’s focus on gifted students, recruitment challenges arose, including limited student availability, classes composed exclusively of gifted students, restricted access, and voluntary participation requirements. These constraints resulted in selecting only one participant: a middle school science teacher at a private school for gifted students aged 6–14. She held a bachelor's degree in physics, a master's degree in solid-state physics, and a teaching certificate from a pedagogical formation program. Her three years of teaching experience allowed exploration of how student outcomes and school context influenced her PCK maps.

The Context of the Study

This study was conducted at a private middle school affiliated with the Ministry of National Education and located in the capital city. The school follows the national science curriculum for seventh grade (Ministry of National

Education, 2006), identical to that used in public schools. Still, it enriches and differentiates instruction to meet the needs of gifted students. Participants included twelve seventh-grade students identified as gifted (IQ ≥ 120, WISC-III; Wechsler, 1991) and their science teacher. From a micro-level perspective, the study focused on instructional interactions tailored to the characteristics of gifted learners. At the meso-level, the school context, such as access to laboratories, use of smart boards, collaborative teaching culture, and a supportive parent profile, provided an enriched environment for science instruction. At the macro-level, the curriculum framework and policy flexibility allowed private institutions to adapt instruction while adhering to national standards.

Subject and Topic Selections

Two physics topics—work/energy and simple machines—from the seventh-grade science curriculum's "Work and Movement Unit" were selected to investigate the teacher’s PCK, as PCK is topic-specific (Çaylak & Çakıroğlu, 2024; Mapulanga et al., 2024). These topics align with the teacher’s physics background, given that strong subject matter knowledge (SMK) significantly influences PCK development (Evens et al., 2018; Magnusson et al., 1999; Shulman, 1986). Teachers with robust SMK are better at effectively applying PCK in classrooms (Boz & Belge-Can, 2020; Oztay & Boz, 2022), particularly in physics education, where content knowledge enhancement is vital (Mazibe et al., 2023). Physics concepts, often abstract, create unique learning challenges (Hammer, 1996; Sarabi & Abdul Gafoor, 2018; Tenzin et al., 2022), requiring teachers to develop alternative pedagogies (Ahtee & Johnston, 2006). Therefore, the selected teacher was expected to demonstrate enriched pedagogical practices and dynamic PCK component interactions. Long-term data collection was employed to accurately capture the complexity and nuances of teachers' PCK interactions, as teachers' PCK is challenging to measure and evaluate (Aydeniz & Kirbulut, 2014; Baxter & Lederman, 1999; Park et al., 2018), and these complexities are often missed in short-term observations (Loughran et al., 2006). Hence, the instruction of these two topics spanned six weeks (three sessions weekly), facilitating a deeper analysis of the teacher’s PCK. Additionally, due to limited existing research on PCK interactions in physics, the chosen topics offered valuable opportunities for detailed investigation.

Data Collection

This study focuses exclusively on classroom observation data to examine interactions among PCK components through the Alternative Mapping Approach (AMA). Classroom observations were selected as the primary data source, as they provide authentic insights into enacted PCK within instructional practice (Baxter & Lederman, 1999). Nineteen 40-minute lessons on two seventh-grade physics topics—work/energy and simple machines—were observed. An observation protocol aligned with Magnusson et al.’s (1999) PCK model guided data collection, and all lessons were audio-recorded.

It is important to note that this study represents a secondary analysis of previously collected data (Çaylak & Çakıroğlu, 2024). The original study adopted a comprehensive qualitative design to explore a teacher’s PCK through multiple data sources—including classroom observations, pre- and post-lesson semi-structured interviews—within the framework of the Refined Consensus Model (RCM) of PCK. However, the present analysis centers exclusively on the teaching phase of ePCK, as captured in classroom observations, to ensure analytical depth and clarity within the scope of the study.

In the original study, pre-lesson interviews explored the teacher's pedagogical planning, including learning goals, instructional strategies, and assessment methods, while post-lesson interviews captured reflections on classroom enactment, student responses, and divergences between planned and actual instruction. Interview protocols were structured around the Content Representation (CoRe) framework (Loughran et al., 2006), and all interviews were audio-recorded and transcribed verbatim. Although these interviews informed the broader understanding of the teacher's PCK, they are not the focus of the present analysis.

To ensure methodological rigor, researchers served as nonparticipant observers (Patton, 2002), positioning themselves unobtrusively at the back of the classroom. Prior to data collection, a two-week familiarization period was conducted to reduce potential observer effects. During this phase, no data were collected, and researchers introduced themselves as pre-service science teachers to minimize student anxiety and promote natural classroom interactions.

Data Analyses

In this study, the data were analyzed using the secondary data analysis approach. Secondary data analysis refers to the re-examination of data that were previously collected and analyzed for a specific primary purpose, with the aim of addressing new research questions or developing alternative perspectives (Cheng & Phillips, 2014; Johnston, 2014). This method allows for the generation of new knowledge by analyzing existing data within different contexts. Similarly, this study employed secondary data analysis to establish a new perspective or conceptual focus. Since the research involves re-examining a portion of existing data from a different perspective, it falls under the "new perspective/conceptual focus" category. In a previous study conducted by the authors (Çaylak & Çakıroğlu, 2024), an in-depth analysis of explicit PCK related to work and energy, simple machines, and frictional force was carried out. The aim of that study was to uncover the knowledge and skills employed by the teacher while working with gifted students. The data used in the earlier study included interviews, classroom observations, card-sorting activities, and lesson plans. The data from the initial study were analyzed using Magnusson et al.'s (1999) PCK model, and the resulting codes and categories were organized into detailed tables. Detailed information about the coding process, the differences between the general science curriculum and the enrichment curriculum contents, and the characteristics of the gifted students can be found in the authors' initial study (Çaylak & Çakıroğlu, 2024). However, in the current study, *only classroom observations* were analyzed to investigate how the teacher's PCK components interact during the teaching process. These observations were examined through content analysis and the constant comparative method.

Content Analysis

This method was employed to capture the interaction of PCK components during the teaching of work/energy and simple machines. Content analysis facilitates the discovery of repetitive words or codes in related data, reducing categories under specific themes and enabling researchers to draw inferences from the data set (Patton, 2002). The first step of content analysis involves determining categories based on the literature (Fraenkel & Wallen, 2009). Accordingly, we began by identifying both predetermined and emerging codes as well as interaction categories, primarily derived from the studies of Park and Chen (2012) and Aydın et al. (2015). These categories represent potential binary interactions within the data set. However, we adapted and refined some categories to align with the context of the present study, introducing new categories to reflect triadic, quadruple, or more complex interactions. Ultimately, we identified ten interaction categories. Table 1 presents the codes and categories representing the interaction of PCK components for this study.

The Constant Comparative Method

This method is utilized in a repetitive process where data collection is followed by a *spiral motion* to abstract concepts or develops theories. The spiral motion involves iterative comparisons between data and data, data and categories, categories and categories, as well as categories and concepts (Bryant, 2013). In this study, the constant comparative method was employed to construct PCK maps by comparing the interactions of PCK components with categories and by comparing categories with one another using an inductive approach. Each interaction code was systematically compared and contrasted with categories derived from Park and Chen's (2012) and Aydın et al.'s (2015) interaction categories. A similar process was used to construct subsequent PCK maps by comparing and contrasting the map of one topic with the map of the next topic.

Table 1. Interaction of the PCK Components' Codes and Their Explanations

Codes	**Explanations**
KoIS-KoA	Employing instructional strategies to evaluate students' foundational knowledge or understanding of concepts.
KoIS-KoL	Addressing misconceptions or gaps in prerequisite knowledge through specific teaching methods. Simplifying abstract ideas by applying targeted instructional techniques. Adopting strategies tailored to overcome learning challenges.
KoIS-STO	Delivering lessons aligned with the teacher's instructional objectives using selected strategies.
KoIS-KoC	Incorporating enrichment curriculum topics into lessons through specific teaching strategies.
KoA-STO	Applying assessment methods to measure whether students have achieved the teacher's intended goals.
KoC-KoL-KoIS	Implementing instructional strategies to address challenges that arise from advanced-level activities.
KoL-KoC-KoIS	Adapting instructional strategies to respond to questions stemming from the needs of gifted learners during advanced activities.
KoIS-KoL-KoIS	While delivering a lesson on a topic through a particular teaching strategy, a learning challenge may arise. To address this challenge, the teacher adapts the instructional

Codes	Explanations
	strategy or incorporates supplementary teaching techniques.
KoIS-KoA-KoL-KoIS	Learning difficulties can arise when questions are asked to conduct an assessment. The teacher addresses these by revising the questions or providing additional explanations.
KoIS-KoC-KoA-KoL-KoIS-KoL-KoIS	The teacher employs a specific instructional strategy to explain an enrichment activity. During the assessment of the activity, learning difficulties may arise. To address these challenges, the teacher provides alternative examples and explanations. If the difficulties persist, the teacher ultimately switches to a different instructional technique.

While constructing the interaction maps of PCK components, classroom observations were analyzed. After identifying the codes and categories related to the interaction of PCK components, the following process was applied: First, we listed the interactions that emerged during the teacher's teaching, step by step, from the beginning to the end of each lesson. For instance, Table 2 presents the sequence of interactions related to the subtopic of potential energy within the broader topic of work and energy. Second, we attempted to place the codes (Table 2) onto a map. The interactions were grouped in a structured manner and arranged on the maps in the most efficient, economical, and space-conserving way. Figure 1 illustrates all the stages of the teacher's instruction on the topic of potential energy.

Table 2. Codes and Explanations of the Potential Energy Interaction Map

Codes	Explanation
KoIS-STO	The teacher used lecturing to present her goals and purposes (explanation of potential energy).
KoIS-KoL	The teacher used a strategy to explain the relationships between potential energy and height, which led to students' learning difficulties.
KoIS-KoA	The teacher asked a question to assess students' performance.
KoIS-STO	The teacher used lecturing to present her goals and purposes (e.g., an explanation of the formula of potential energy).
KoIS-KoL	The teacher used a strategy to explain the relationships between potential energy and mass, which led to students' learning difficulty.
KoC-KoL-KoIS	When the teacher presented upper-class concepts, there was learning difficulty (KoC-KoL), so the teacher tried to handle this to change her strategy.
KoIS-STO	The teacher used lecturing to present her goals and purposes (e.g., explanation of symbols and units for the formula of potential energy).
KoL-KoC	The students queried about extra curriculum topics to extend the teacher's explanation.

The map, in Figure 1, consists of two concentric circles with five PCK components (KoIS, KoL, KoC, KoA, and STO) placed at the center. The circular band between the two rings is divided into four distinct teaching segments (the number of segments varies from other maps as it is specific to the subject); each representing a section of the lesson and indicating which component initiated the interaction within that segment. For instance, in Segments 1 and 3, the interaction was initiated by the KoIS component, while in Segment 2 it was KoC, and in Segment 4 it was KoL.

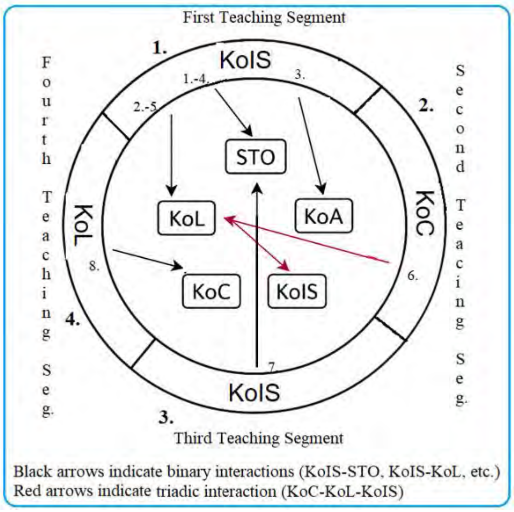


Figure 1. Potential Energy Interaction Map

The interactions are visualized through arrows that illustrate how the teacher's knowledge and skills influenced each other throughout the teaching process. Black arrows represent binary interactions, whereas red arrows indicate triadic interactions. The interactions are numbered to reflect the sequence in which they occurred within each segment. For example:

- Teaching Segment 1 includes five interactions. In this segment, KoIS functioned as the initiating component, and the interactions primarily involved the relationship between KoIS and STO or other components. In particular, Interactions 1 and 4 demonstrate that the teacher employed specific instructional strategies (KoIS) in order to achieve instructional objectives (STO). Detailed explanations of each binary interaction are provided in Table 2.
- Teaching Segment 2 contains only one interaction: Interaction 6, which is a triadic interaction (KoC–KoL–KoIS). This occurred when the teacher recognized student learning difficulties (KoC–KoL) while introducing advanced concepts and responded by modifying her instructional strategy.
- Teaching Segments 3 and 4 each include one interaction. The segmentation was based on changes in the initiating component throughout the teaching process. This classification helped to illustrate the temporal progression of instruction and facilitated the tracking of transitions among components.

Finally, we analyzed two topics and constructed 12 PCK maps by comparing and contrasting each map based on the teacher's instruction on work and energy (*work, kinetic energy, potential energy, and conservation of energy*) and simple machines (*simple machines, levers, pulleys, hoists, inclined planes, spinning wheels, gears, and hoops*). Through the constant comparative method, we were able to identify common patterns in the teacher's instruction, focusing on the interaction of PCK components as depicted in the maps.

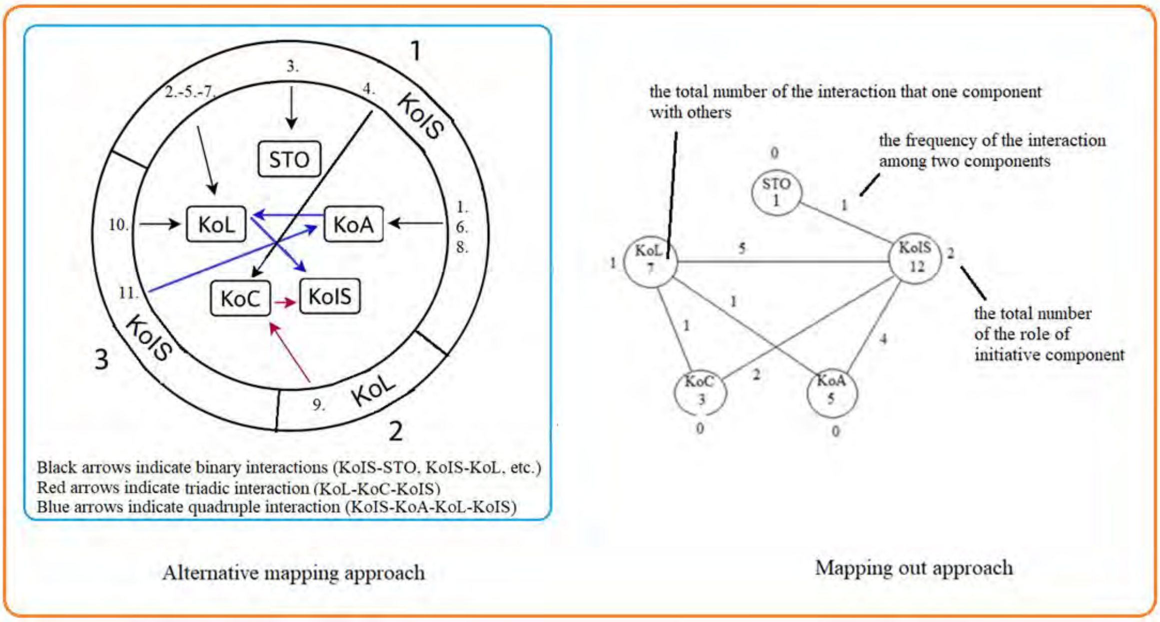
To ensure the trustworthiness of this study, we employed triangulation (data, investigator, and method) (Patton, 2002), long-term observation, peer debriefing (Cresswell, 2007), and member checks (Merriam, 2009) to enhance the credibility of the findings. Interrater reliability for defining interaction codes in the construction of PCK maps based on observational data yielded a 79% agreement rate, while interrater reliability for data collection using the observation protocol resulted in an 85% agreement rate. These scores can be considered sufficient indicators of the study's trustworthiness (Miles & Huberman, 1994).

Findings

After conducting detailed data analyses, we constructed 12 PCK maps (see some maps in the Appendix) using the AMA approach. These maps include binary, triadic, and more complex interactions among components, with the codes and their explanations provided in Table 1. Based on these maps, the findings of this study suggest four key assertions, as outlined below.

The Alternative Mapping Approach (AMA) Provides More Detailed and Complex Interactions

At first, we considered using Park and Chen's mapping-out approach. After applying their (2012) coding scheme and creating initial PCK maps, we found that key pedagogical elements—like how the teacher addressed learning difficulties—were missing. The mapping-out method limited us to binary interactions (e.g., KoC-KoL, KoIS-STO) and their frequencies, offering only a general overview of component use without capturing instructional details. To better portray the teacher's PCK, we needed a step-by-step representation of her teaching throughout the lesson. This led us to develop the AMA used in this study. Figure 2 compares the two approaches, using the work and energy topic as an example.



Black arrows indicate binary interactions (KoIS-STO, KoIS-KoL, etc.)
Red arrows indicate triadic interaction (KoL-KoC-KoIS)
Blue arrows indicate quadruple interaction (KoIS-KoA-KoL-KoIS)

Alternative mapping approach

Mapping out approach

Figure 2. Interaction Maps of Work and Energy

The AMA approach made it possible to clearly trace the sequence and complexity of PCK interactions, enhancing interpretation of the teacher's practices. For example in Figure 2, the teacher began by using questions to assess prior knowledge (KoIS-KoA), then addressed misconceptions (KoIS-KoL), explained key concepts (KoIS-STO), and introduced formulas and examples (KoIS-KoC). These led to further learning difficulties (KoIS-KoL), prompting additional explanations and follow-up questions (KoIS-KoA, KoIS-KoL). She reintroduced the same problem to reassess understanding (KoIS-KoA) and, when confusion persisted, used enriched activities (KoL-KoC-KoIS). After further clarification attempts (KoIS-KoL), she adapted her explanation again, yet students still struggled. This resulted in a final instructional cycle involving multiple components (KoIS-KoA-KoL-KoIS). In sum, the AMA enabled a detailed, step-by-step view of how the teacher's PCK evolved during instruction, capturing not only complex interactions—triadic, quadruple, and beyond—but also the initiating components driving them.

Students' Outcomes Shape the Interactions

The study found that student outcomes, reflected in KoL, had a strong impact on the teacher's PCK. KoL included three subcomponents: knowledge of student difficulties, misconceptions, and characteristics of gifted students (e.g., need for enrichment). These subcomponents interacted with other PCK elements in different ways. KoIS-KoL links showed how instructional strategies sometimes led to learning difficulties. KoL-KoC interactions revealed the teacher's efforts to adapt activities for gifted students. KoA-KoL appeared during assessments, where learning gaps became visible. Overall, these subcomponents actively influenced the teacher's instructional decisions throughout the teaching process.

Figure 2 (work and energy) illustrates two types of KoL interactions. In the 2nd interaction, the teacher asked about the concept of work, and students incorrectly replied, "work is anything someone does in daily life." Here, KoIS interacted with KoL, specifically addressing misconceptions. In the 9th interaction, when students were unsatisfied with the explanation, the teacher adapted her instruction using enrichment content—first engaging KoL (gifted student characteristics), then KoC (curriculum knowledge), and finally KoIS (presenting mathematical problems). In the 11th interaction, KoL related to learning difficulties became evident. The teacher assessed understanding (KoIS-KoA); when students struggled (KoA-KoL), she adjusted her strategy (KoL-KoIS).

The teacher's 12 PCK maps show notable differences in interaction number, variation, and complexity. Even for related physics topics like kinetic (Figure 3) and potential energy (Figure 1), the maps vary. Figure 3 displays more and more complex interactions than Figure 1. Student outcomes—such as understanding, difficulties, or enrichment needs—significantly influenced instructional decisions. For example, the kinetic energy topic included 12 interactions, with two being triadic, while potential energy involved 8 interactions and one triadic. Although both topics were similar in content and complexity, the order of instruction (kinetic taught first) also affected the structure of the maps.

Furthermore, students were able to transfer their prior learning about kinetic energy to the topic of potential energy, reducing the instructional challenges faced by the teacher when teaching potential energy. Once meaningful and robust connections were established between kinetic and potential energy, students found it easier to comprehend the topic of conservation of energy. As shown in Figure 4, the conservation of energy topic included just three interactions, requiring minimal effort from the teacher.

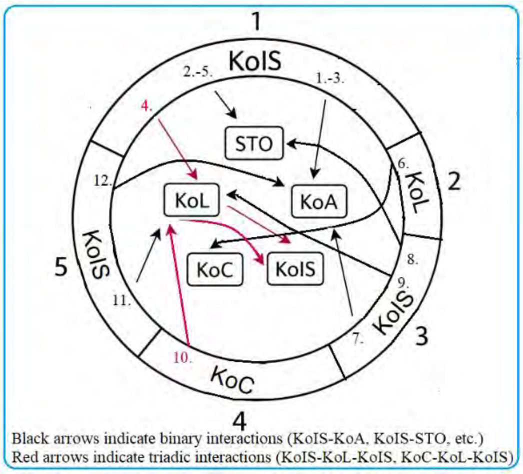


Figure 3. Interaction Map of Kinetic Energy

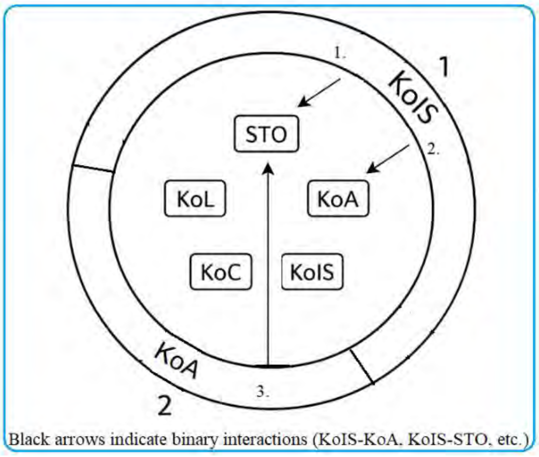


Figure 4. Interaction Map of the Conservation of Energy

This finding is also reflected in the teaching of simple machines. The teacher covered the topics in this order: levers, pulleys, hoists, inclined planes, spinning wheels, gears, and hoops (see Appendix). Levers and pulleys each involved over 10 interactions, while the others had fewer than 5. Students struggled more with levers and pulleys, as these were taught first and required grasping core concepts. Once they understood the relationship between force and load, they could transfer this knowledge to later topics like inclined planes and gears, resulting in fewer instructional challenges for the teacher.

The Interaction Maps Explain the Teacher's Teaching Practices (Teaching Phase of ePCK)

Since this study focused solely on the teacher’s teaching process, the teacher’s interaction components predominantly began with KoIS. Asking questions, explaining phenomena, presenting lectures, or solving problems were all pedagogical applications that represented topic-specific strategies employed by the teacher. After initiating the lesson with KoIS, students’ outcomes—such as learning difficulties, unclear points, or misconceptions—shaped the direction, type, and complexity of subsequent interactions.

When analyzing the PCK maps, KoIS emerged in two distinct ways. First, KoIS functioned as an initiating component (represented by the circular band between the two rings) to begin interactions with other components. This pattern was observed consistently across all PCK maps. Figure 5 serves as an example illustrating the role of KoIS as an initiating component.

According to Figure 5, the teacher began her lesson by explaining hoops and their features using visual materials and models (KoIS-STO). Next, she posed a question about hoops and their attachment pattern to assess her students’ understanding (KoIS-KoA). Finally, she asked a question about hoops and their rotational shapes to evaluate her students’ performance (KoIS-KoA). In all three of these interactions, KoIS initiated the interaction with other components.

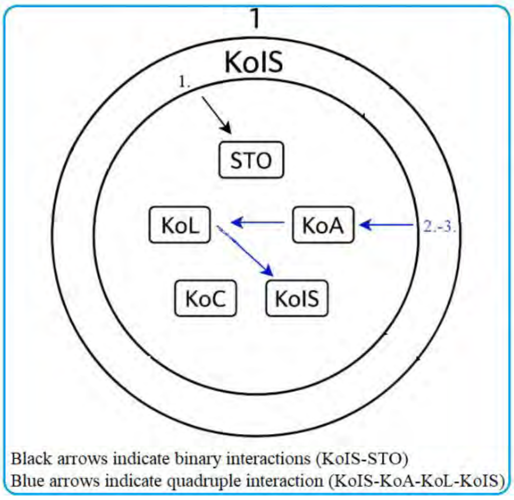


Figure 5. Interaction Map of Hoops

The second observation is that KoIS also functioned as a general interacting component (represented by one of the 5 components in the middle of the shape) when learning difficulties arose. Figure 5 indicates that, in response to learning difficulties, the teacher adjusted her teaching by introducing new questions, examples, or other pedagogical strategies. Through this process, the teacher utilized her KoIS to enhance or support her students' understanding. For instance, as shown in the second and third interactions in Figure 5 (KoIS-KoA-KoL-KoIS), the teacher modified her teaching strategy because students struggled to fully comprehend her questions and explanations.

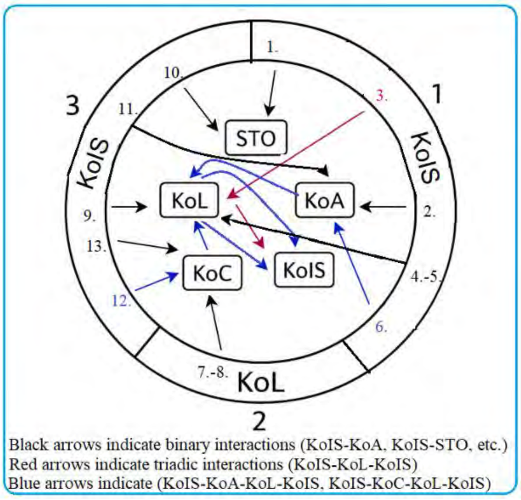
Contextual Factor in the Maps

In this study, 7th-grade physics topics were taught by the teacher, including the concepts of work/energy and simple machines, which are part of the middle school science curriculum. During the teaching process, the teacher extended some concepts to include upper-level topics from the high school curriculum, incorporating advanced concepts and materials coded as knowledge of the enrichment curriculum. Since the students were gifted, the classroom environment differed significantly from that of typical 7th-grade classrooms with non-gifted students. The interaction of the teacher's PCK components within this unique context, as well as the ways in which contextual factors shaped the interaction maps, are clearly outlined below.

KoC was not a highly active component during the teaching of physics topics. Its interactions with other components were observed in four connections: KoL-KoC, KoC-KoL, KoIS-KoC, and KoC-KoA. The teacher utilized her knowledge when students, being gifted, requested extracurricular knowledge and activities, as they required enrichment activities. Since these students easily understood the teacher's explanations, they often needed alternative activities to fill the remainder of the class time. Consequently, the teacher had to design or adapt new applications and activities to address their needs, which were coded as enrichment activities derived from high school science curricula. In such situations, when students sought alternative activities or raised questions requiring more in-depth knowledge, KoL interacted with KoC.

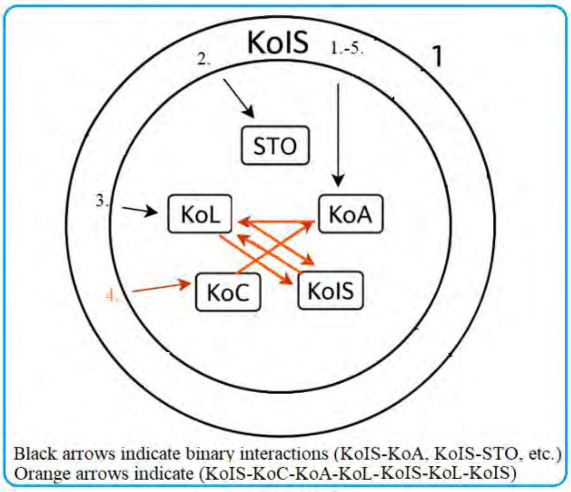
During this process, the teacher combined her knowledge of both the high school and middle school science curricula to provide appropriate enrichment activities. For example, in Figure 3 (kinetic energy—6th interaction), after the teacher explained kinetic energy and its variables, some students struggled to comprehend her explanation and asked for more concrete examples (KoL-KoC). Because of their gifted characteristics, the students did not accept the initial explanation and requested additional examples. In response, the teacher presented the formula for kinetic energy. However, after presenting the formula, learning difficulties emerged as the students attempted to solve related problems (KoC-KoL, 10th interaction). These two types of interactions—KoL-KoC and KoC-KoL—frequently appeared in the interaction maps.

In some cases, after completing the teaching of related concepts, the teacher introduced problems or questions related to upper-level topics, resulting in an interaction between KoIS and KoC. To illustrate this interaction, Figure 6 provides insight into the 13 interactions within the Pulleys topic. At the end of the class, fixed and movable pulleys were connected in a complex arrangement, and the relationship between force and load was calculated—a concept presented in the high school curriculum.



Black arrows indicate binary interactions (KoIS-KoA, KoIS-STO, etc.)
Red arrows indicate triadic interactions (KoIS-KoL-KoIS)
Blue arrows indicate (KoIS-KoA-KoL-KoIS, KoIS-KoC-KoL-KoIS)

Figure 6. Interaction Map of Pulleys



Black arrows indicate binary interactions (KoIS-KoA, KoIS-STO, etc.)
Orange arrows indicate (KoIS-KoC-KoA-KoL-KoIS-KoL-KoIS)

Figure 7. Interaction Map of Hoist

The final interaction involving KoC was observed in connection with KoA. In Figure 7, during the 4th interaction in the hoist map, the teacher demonstrated examples of hoists and their connection parts and posed questions to assess the students' understanding (KoC-KoA, 4th interaction). However, some students struggled to grasp the teacher's explanation, leading to learning difficulties. To address these difficulties, the teacher employed alternative examples and explanations. Unfortunately, despite these efforts, learning difficulties persisted. As a last step, the teacher attempted to clarify the phenomena using additional instructional strategies.

Discussion

This study explored how a science teacher's PCK components interacted while teaching work/energy and simple machines. A revised version of Park and Chen's (2012) mapping-out approach, called the "Alternative Mapping Approach" (AMA), was introduced to capture these interactions in greater detail. AMA revealed which components interacted, how often, and how student outcomes and other components influenced the teacher's practices. Unlike previous approaches that emphasized quantity (Park & Chen, 2012), AMA also shed light on the quality of these interactions, offering a richer view of PCK. Rather than isolating components, AMA focused on their dynamic interplay, enhancing our understanding of teachers' PCK. The maps created show how components interact across the lesson, each with distinct, directional flows. Unlike earlier studies (e.g., Şen, 2023), which often lacked directionality, AMA clarified which component initiated an interaction and which responded, offering a clearer picture of instructional reasoning.

Gess-Newsome (2015) conceptualized PCK as both static (planning and reasoning) and dynamic (instructional practice). AMA captures what occurs during the dynamic phase of enacted PCK, aligning with Carlson and Daehler's Refined Consensus Model (2019). From this view, AMA serves as a useful tool for analyzing and tracking classroom practices within the ePCK domain. While the RCM outlines key elements of PCK, it does not clearly explain how teachers develop PCK, adapt instruction, or integrate various knowledge bases (Carlson & Daehler, 2019). Nor does it explicitly link student learning to teachers' PCK. In contrast, AMA demonstrates that student responses play a significant role in shaping teachers' PCK through component interactions.

This study presented four assertions with supporting evidence, offering a new lens for understanding PCK. *The first assertion introduced the AMA*, showing that the teacher's PCK interaction maps were both topic- and concept-specific. PCK research often focuses on either topic (Galimova et al., 2023; Ottogalli & Bermudez, 2024) or concept levels (Carlson & Daehler, 2019). Even within physics, PCK levels vary across topics (Mazibe et al., 2023). Each map generated through AMA was unique, reflecting concept-based interactions. These maps differed in interaction frequency (3 to 13) and complexity (binary, triadic, or more). Although the teacher used a consistent teaching approach, the maps varied, supporting the view that science topics—especially in physics—differ in abstraction and complexity (Ahtee & Johnston, 2006; Hammer, 1996; Loughran et al., 2006). These differences may stem from variations in subject matter knowledge (Mazibe et al., 2023), leading to distinct learning and teaching challenges, which appeared as diverse and complex PCK interactions.

The second key finding concerned how student outcomes shaped the teacher's PCK maps. KoL was the second most interactive component after KoIS. Three KoL subcomponents—awareness of student difficulties, misconceptions, and characteristics of gifted students—posed significant instructional challenges. Addressing misconceptions requires intentional integration of conceptual strategies (Buma & Nyamupangedengu, 2023). Alongside these, the abstract and complex nature of some physics topics (Ahtee & Johnston, 2006; Hammer, 1996) contributed to learning difficulties, which are integral to teaching practice (Loughran et al., 2006). Each challenge triggered KoL interactions with all components except STO. Similarly, Aydın and Boz (2013) found KoL and KoIS to be the most interactive during instruction. Teachers adjust their teaching in response to students (Lertdechapat & Faikhamta, 2025), for instance, by clarifying misunderstood concepts or using alternative strategies. When students misuse scientific terms, teachers often pose new, definition-focused questions (Lertdechapat & Faikhamta, 2025). Bayram-Jacobs et al. (2019) also emphasized recognizing student difficulties and selecting appropriate strategies as central to PCK development. KoL and KoC frequently interacted when addressing prior knowledge and misconceptions, a link also observed in over half of Padilla and van Driel's (2011) participants.

The third major finding highlighted KoIS as a central component across all interaction maps. KoIS appeared throughout the teaching process as an initiating element, encompassing the teacher's speech, demonstrations, explanations, and questions—often tied to topic-specific strategies. Similar to earlier studies, KoIS and KoL were frequently active and interacted with other components such as KoC, KoA, and STO (Aydın & Boz, 2013; Park & Chen, 2012). Park and Chen (2012) also observed that KoIS and KoL guided other components. Suh and Park (2017) reported strong triangular connections among STO, KoL, and KoIS, accounting for over 60% of the interactions. This was attributed to teachers shaping KoIS based on their understanding of student learning challenges. The strong STO-KoIS and STO-KoL interactions underscore STO's influence on both components. In contrast, Akın and Uzuntiryaki-Kondakci (2018) found KoC also played a central role alongside KoIS and KoL. However, Friedrichsen et al. (2009) reported fewer KoIS interactions, possibly due to their reliance on lesson plans and interviews, which may not fully capture instructional practices. In this study, observation-based data emphasized KoIS's prominence in the enactment phase. Aydın and Boz (2013) supported this by categorizing PCK interactions into three episodes: understanding, decision-making, and enactment. While KoL, KoC, and STO were dominant during planning, KoIS and KoA were more active during instruction. Overall, the strength of KoIS-KoL interactions varies by context. Teacher educators often recognize students' learning difficulties but may not adjust strategies accordingly (Ottogalli & Bermudez, 2024), leading to weaker KoIS-KoL links. In contrast, pre-service teachers tend to respond more effectively to student needs, resulting in stronger interactions (Sæleset & Friedrichsen, 2021).

AMA-generated maps showed that KoA interacted with all other components to varying degrees and was frequently used by the teacher. This underscores AMA's strength in capturing PCK interactions. In contrast, earlier studies reported KoA as the least interactive component (Aydın & Boz, 2013; Aydın et al., 2015; Bayram-Jacobs et al., 2019; Ottogalli & Bermudez, 2024). Şen et al. (2022) found that experienced teachers showed more KoA interactions, while novice teachers showed fewer—likely due to the evolving nature of assessment knowledge (Sickel & Friedrichsen, 2018). Bayram-Jacobs et al. (2019) also noted KoA as the least developed PCK domain. One reason may be that teachers often focus on content delivery, neglecting assessment processes (Barendsen & Henze, 2019), and typically associate assessment with exams and end-of-unit tasks (Ottogalli & Bermudez, 2024), leading to its limited presence in maps. However, Park and Chen (2012) highlighted KoA's active role in practice, especially its strong ties to KoL and KoIS. These links stemmed from teachers' frequent use of informal assessments, such as questioning or observing performance. Similarly, in this study, the teacher assessed students' understanding through informal strategies, leading to prominent KoA interactions in AMA maps.

The fourth key finding concerned KoC, especially its role in enrichment activities. Although KoC interacted with KoL, KoIS, and KoA (but not STO), these interactions were limited, showing that KoC was less active than KoIS and KoL. This supports prior findings by Park and Chen (2012) and Reynolds and Park (2021), who also found KoC to be the least interactive component during teaching. However, KoC showed more activity during planning stages, particularly among preservice teachers, where its interaction with other components developed significantly (Aydın et al., 2015). Student-related factors—such as misconceptions, prior experiences, personality traits, and cognitive development—are essential in the teaching-learning environment. As a result, students' knowledge strongly shapes teachers' ePCK (Carlson & Daehler, 2019). Responding to Park and Suh's (2019) call to adapt the mapping-out approach to better reflect how student outcomes affect teaching, this study identified the characteristics of gifted students as a major contextual factor influencing ePCK.

Conclusion and Limitations

This study introduced the Alternative Mapping Approach (AMA) to visualize how a science teacher's PCK components interact during instruction. AMA allowed us to track which components were connected throughout each physics lesson from start to finish. Notably, it revealed not only the presence of binary interactions but also more complex patterns, such as triadic, quadruple, and higher-order interactions. In addition, AMA clarified the directionality of these interactions—indicating which component initiated each interaction—and captured the temporal sequence in which interactions unfolded during the lesson. These capabilities enhanced the interpretation of the teacher's enacted PCK by going beyond simple interaction frequency and student outcomes. Ultimately, AMA provided a more comprehensive and dynamic understanding of the structure and flow of PCK components within classroom teaching.

Despite its strengths, this study has two key limitations. First, based on Magnusson *et al.'s* (1999) definition, STO includes teachers' goals, general views of science teaching, and, as expanded by Friedrichsen and Dana (2005), their understanding of the Nature of Science (NOS). In this study, while the teacher showed a conceptual grasp of teaching goals, she did not emphasize science process skills or NOS, so the latter two subcomponents were absent from the AMA-based PCK maps. This omission was due to the study's reliance on classroom observations, which did not capture these aspects. The second limitation concerns KoC. Defined as knowledge of concepts, objectives, and limitations in physics, KoC in this study was coded based on enrichment activities involving advanced concepts and materials. Thus, its original scope wasn't fully reflected in the AMA. Addressing these limitations, future research can refine AMA further. As an analytic tool, it holds promise for making the abstract structure of the RCM model more concrete and understandable, advancing PCK research.

Statements and Declarations

Acknowledgments: This study is derived from a part of the first author's doctoral dissertation.

Notes: The authors used *ChatGPT-5* (OpenAI, 2025) as an AI-based tool to assist with language editing and improvement of the English text. All final edits were carefully reviewed and approved by the authors, who take full responsibility for the accuracy and integrity of the manuscript's content.

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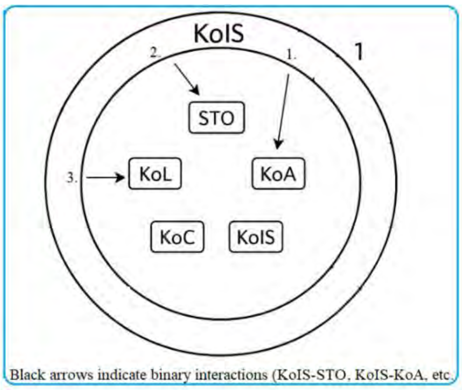
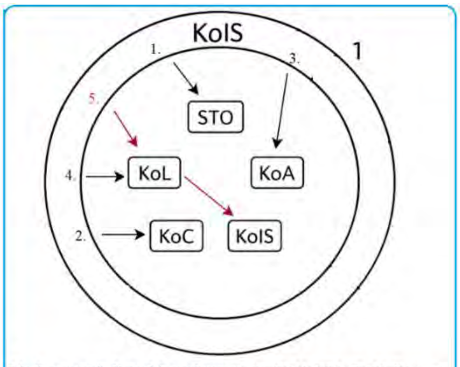
Appendix

Simple Machines



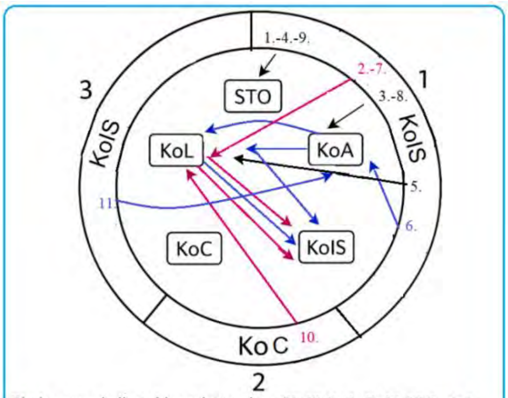
Black arrows indicate binary interactions (KoIS-STO, KoIS-KoA, etc.

Gears



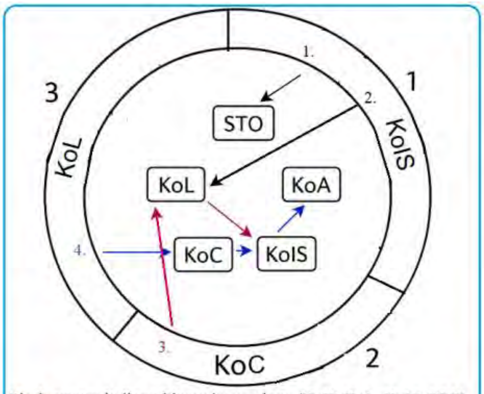
Black arrows indicate binary interactions (KoIS-STO, KoIS-KoA, etc.
Red arrows indicate triadic interactions (KoIS-KoL-KoIS)

Levers



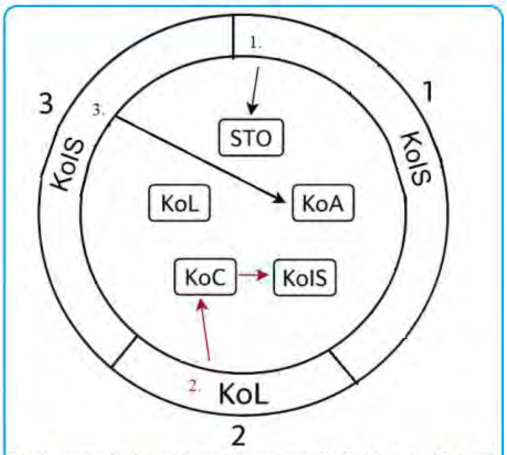
Black arrows indicate binary interactions (KoIS-KoA, KoIS-STO, etc.)
Red arrows indicate triadic interactions (KoIS-KoL-KoIS, KoC-KoL-KoIS)
Blue arrows indicate quadruple interaction (KoIS-KoA-KoL-KoIS)

Inclined Plane



Black arrows indicate binary interactions (KoIS-KoL, KoIS-STO)
Red arrows indicate triadic interactions (KoC-KoL-KoIS)
Blue arrows indicate quadruple interaction (KoL-KoC-KoIS-KoA)

Spinning Wheel



Black arrows indicate binary interactions (KoIS-KoA, KoIS-STO)
Red arrows indicate triadic interactions (KoL-KoC-KoIS)