

Promoting knowledge integration in work and mechanical energy through conceptual framework and cooperative learning instruction

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(Received 24 January 2025; accepted 6 June 2025; published 27 June 2025)

Achieving knowledge integration for deep learning requires students to construct well-connected knowledge structures by understanding and applying the central ideas of a concept. However, research on student learning in work and mechanical energy reveals persistent challenges in grasping fundamental concepts, particularly in connecting the work-energy theorem, potential energy, and the principle of conservation of mechanical energy. This study investigates the effectiveness of two instructional interventions based on the conceptual framework of work and mechanical energy: one employing lecture-based instruction and the other incorporating a cooperative learning approach. The findings provide strong evidence that the conceptual framework is an effective tool for guiding instruction to promote knowledge integration. Additionally, the use of cooperative learning instruction was shown to further enhance students' ability to connect concepts and develop deep understanding, offering valuable insights for designing instructional strategies aimed at fostering knowledge integration.

DOI: [10.1103/lj4w-wsqb](https://doi.org/10.1103/lj4w-wsqb)

I. INTRODUCTION

Developing a deep conceptual understanding of physics is a fundamental goal of science education [1–6], yet achieving it remains a persistent challenge. Research has consistently demonstrated that traditional teaching methods often fail to cultivate the integrated knowledge structures necessary for expertlike reasoning and problem solving [7–9]. Instead, students frequently resort to rote memorization and procedural strategies, which may yield success on standard textbook problems but often fail to prepare them for addressing tasks in novel contexts and/or with complex concepts [10,11]. For instance, while traditional instruction enables many students to routinely solve numerical problems, it often falls short in fostering their understanding of the underlying principles or applying these concepts in unfamiliar contexts [12]. This approach frequently results in fragmented knowledge structures, where isolated pieces of information are tied to specific contexts rather than forming a cohesive, transferable framework of understanding [8,13].

These findings highlight the pressing need for instructional strategies that emphasize knowledge integration.

To facilitate deep conceptual understanding in physics education, it is essential to model students' conceptual progress using the knowledge integration perspective [14]. According to Linn, when students achieve a profound understanding of scientific concepts, their knowledge structures evolve from fragmented organizations into well-integrated systems. This process of reorganizing discrete pieces of information into broadly applicable principles is known as knowledge integration [15]. In recent years, the conceptual framework model has been developed specifically to address the knowledge integration process in physics education [16–18]. This model offers a concrete application of the knowledge integration perspective, providing a tool that explicitly models the knowledge structures of students as they transition from novices to expert learners. It emphasizes content-specific knowledge, with conceptual frameworks established for various physics topics such as light interference [17], Newton's third law [19], wave propagation [20], simple electric circuits [21], work and mechanical energy [22], electromagnetic induction [23], and galvanic cell [24]. These frameworks guide the development of assessment instruments that probe students' reasoning and measure the depth of their knowledge integration.

Beyond assessment, the conceptual framework model also serves as a valuable tool for designing targeted instructional interventions [16,17,20,25,26]. By explicitly connecting isolated pieces of information to the central idea

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of each concept, it helps students organize their fragmented knowledge into a cohesive, integrated structure. This process fosters a deeper conceptual understanding, moving students beyond rote memorization to facilitate the development of transferable knowledge. In this way, the conceptual framework model plays a critical role in fostering students' deep understanding of physics, ensuring that learning is both meaningful and applicable across different contexts. However, most conceptual-framework-based instructional interventions to date have been implemented using traditional lecture-based teaching methods. Whether changes in teaching methods can influence the effectiveness of knowledge integration has yet to be investigated.

In our previous study, we developed a conceptual framework model for work and mechanical energy, which provided the foundation for designing a knowledge integration assessment tool for this topic [22]. This tool was used to evaluate students' conceptual understanding and levels of knowledge integration in work and mechanical energy. Building on this framework, the present study seeks to design and implement an instructional intervention aimed at promoting knowledge integration in students' learning of work and mechanical energy. In addition, following the recommendations of Xu *et al.* [25], the study incorporates cooperative learning or inquiry-based instructional strategies to investigate the impact of combining conceptual-framework-based instruction with cooperative learning methods. Accordingly, this study addresses two research questions:

RQ1: To what extent can conceptual-framework-based instructional interventions enhance students'

knowledge integration in the topic of work and mechanical energy?

RQ2: To what extent does incorporating a cooperative learning method improve students' knowledge integration?

II. METHODS AND DESIGN

A. The conceptual framework of work and mechanical energy

In our previous study, the conceptual framework of work and mechanical energy was developed and applied to assess students' knowledge integration. This framework illustrates a general progression of knowledge integration from fragmented structures to integrated ones, as shown in Fig. 1 [22]. In this process, establishing a good understanding of the central idea, the work-energy theorem, plays an essential role in integrating the different knowledge components. The arrows linking the different contextual, conceptual, and outcome components represent reasoning pathways of experts and novices. Solid arrows indicate the reasoning pathways of experts, while dashed arrows represent the possible thinking pathways of novices.

The conceptual framework model of work and mechanical energy was used to guide the design of an assessment tool aimed at measuring students' level of knowledge integration. Based on the assessment and interview outcomes, student understanding of work and mechanical energy was categorized into three progressive levels of knowledge integration: novice (0–40), intermediate (40–80), and expertlike (80–100) [22], where the numerical ranges in the brackets

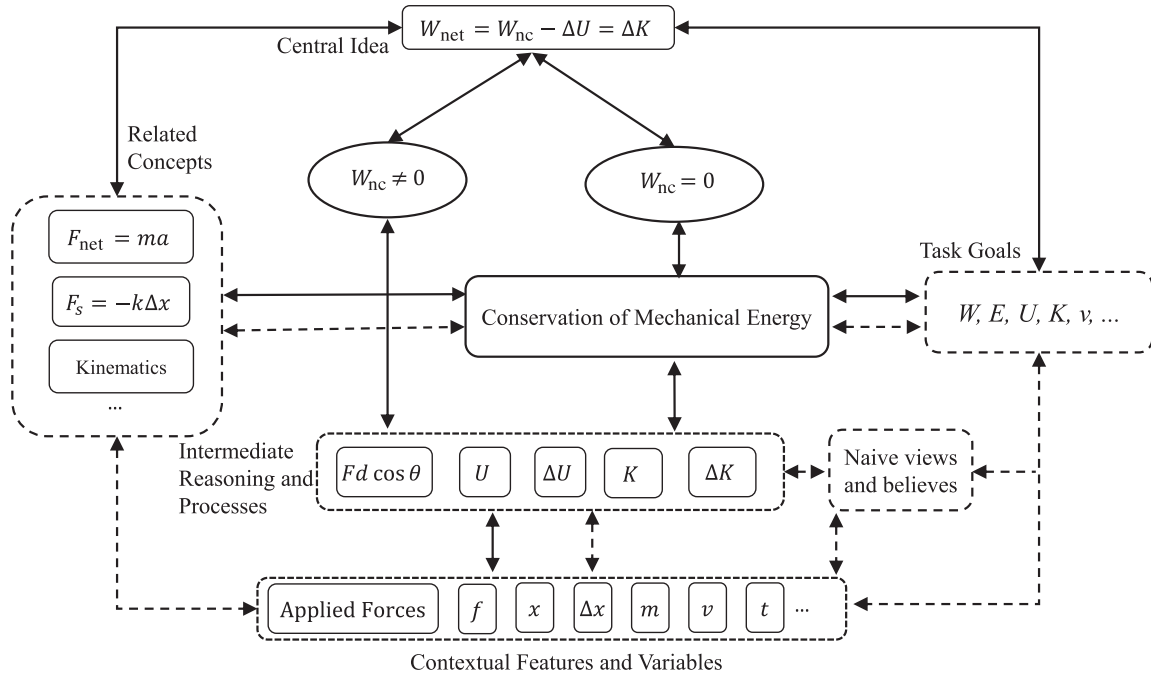


FIG. 1. Conceptual framework of work and mechanical energy.

indicate the percentage score ranges for the corresponding knowledge integration levels. Students at different levels of knowledge integration exhibited distinct types of reasoning pathways that could be mapped in the conceptual framework of work and mechanical energy. Students at the novice level appeared to lack an understanding of the central idea, and their knowledge structures were fragmented, with no connections to the central idea. Students at the intermediate level appeared to have developed a basic understanding of the central idea and could apply it in familiar contexts. The knowledge structures of these students were partially integrated, with some connections to the central idea. Students at the expertlike level showed a strong understanding of the central idea and had developed a well-integrated knowledge structure anchored by the central idea.

The conceptual framework of work and mechanical energy, as demonstrated in previous research, has been shown to be effective for modeling and analyzing knowledge integration in this content topic. As a result, the framework is applied in the current study to guide the design of instructional interventions aimed at promoting knowledge integration.

B. Instructional designs of work and mechanical energy

This study employed three distinct instructional designs, each tailored to address different aspects of instruction and evaluate their impact on learning effectiveness. Design 1 followed a traditional lecture-based instructional approach, structured according to the physics curriculum standards and textbook. It did not emphasize conceptual connections and was used as the control group to provide a baseline for comparing the interventions in the other two groups. Design 2 introduced a conceptual-framework-based lecture approach, focusing on the central idea of the work-energy theorem and its integration with other physics concepts. This design retained the lecture format but explicitly aimed to evaluate the impact of emphasizing conceptual connections on student learning. Design 3 expanded upon design 2 by incorporating a cooperative learning approach, encouraging collaborative learning and active student engagement to further promote knowledge integration. This design evaluated the effectiveness of combining conceptual-framework-based instruction with a cooperative learning method, altering both the instructional content and teaching approach.

1. Design 1: Traditional instruction design

In China, all school curricula were required to follow the national curriculum standard. The physics course in this study was based on the 2020 high school physics curriculum standard, which was published by the Ministry of Education of China. It outlined the following content requirements for mechanical energy and its conservation principle [27]:

- Understand work and power, and recognize the significance of machine power in production and daily life.

- Understand kinetic energy and the work-energy theorem, and be able to apply the work-energy theorem to explain phenomena in both production and daily life.
- Understand gravitational potential energy, including the relationship between changes in gravitational potential energy and the work done by gravity, and have a qualitative understanding of elastic potential energy.
- Verify the principle of conservation of mechanical energy through experiments, understand the concept of conservation, and appreciate the importance of the concept of conservation in understanding physical laws. Be able to use the principle of conservation of mechanical energy to analyze related problems in production and daily life.

In the physics textbook commonly used in Chinese high schools, the principle of conservation of mechanical energy was covered in five sections [28]:

- Work and power.
- Gravitational potential energy.
- Kinetic energy and the work-energy theorem.
- The principle of conservation of mechanical energy.
- Experiment: verification of the principle of conservation of mechanical energy.

This demonstrated that the principle of conservation of mechanical energy held a central position in both the physics curriculum standard and textbook. Concepts such as kinetic energy, gravitational potential energy, and elastic potential energy were foundational to deriving the principle of conservation of mechanical energy but were considered as supporting concepts without a central focus. Based on a review of the high school physics curriculum standard, existing textbooks, and teachers' instructional design guides, it was observed that the instruction for this topic primarily employed a lecture-based approach. The existing curriculum also expected that, after the instruction, students would be able to construct a concept map similar to the one shown in Fig. 2.

Figure 2 illustrates the instructional sequence and conceptual structure for the unit on work and mechanical energy, which was based on the existing curriculum and textbook. As can be seen from the diagram, while the concept of work was introduced, it was not effectively connected to potential energy, which may result in a fragmented understanding of their relationship. Additionally, the teaching of the principle of conservation of mechanical energy largely focused on memorizing its equation, rather than providing a meaningful derivation or explanation of why mechanical energy is conserved. This lack of connections and mechanistic explanations within the curriculum can lead to fragmentation in students' knowledge, limiting their ability to integrate these concepts into a cohesive framework and understand the fundamental principles underlying energy conservation.

In the instructional phase, teachers used example problems from the textbook to illustrate key concepts. For homework, accompanying workbooks that had been in

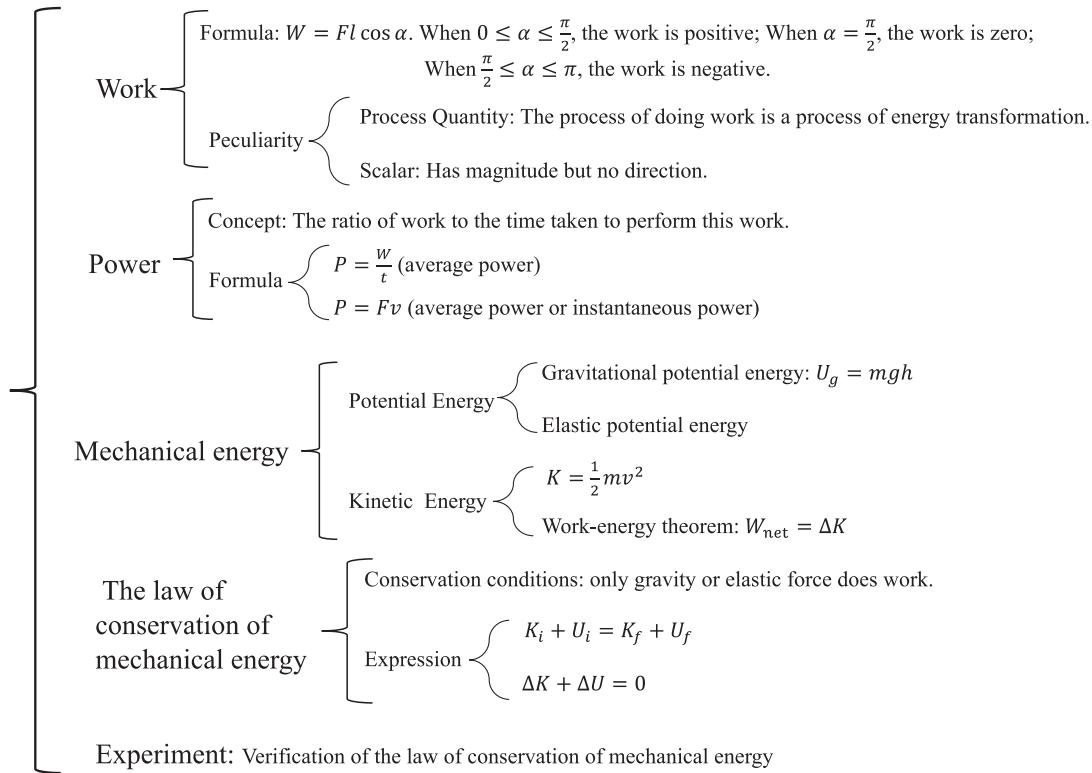


FIG. 2. Concept map of work and mechanical energy.

long term use at the school were assigned for each lesson. During unit review, the concept map depicted in Fig. 2 was introduced to students to consolidate learning outcomes.

2. Design 2: Conceptual-framework-based lecture instruction

Building on the conceptual framework of work and mechanical energy, this instructional design emphasized the central idea of the work-energy theorem, highlighting its connections to other conceptual principles, and focusing on the applicability of physical principles in problem-solving contexts. To achieve this, the instructional content and sequence were modified as shown below:

- Work and power.
- Kinetic energy and the work-energy theorem.
- Experiment: exploration of the work-energy theorem.
- Gravitational potential energy and elastic potential energy.
- The principle of conservation of mechanical energy.

In this instructional sequence, kinetic energy and the work-energy theorem were introduced before potential energy to emphasize the central role of the work-energy theorem. Similarly, in terms of content, to further highlight its importance, the experiment verifying the principle of conservation of mechanical energy was replaced with an experiment exploring the work-energy theorem. In this design, the teaching method was maintained to be in a lecture-based format throughout the instruction.

In both classroom exercises and homework assignments, each section now incorporated atypical context questions (see Supplemental Material [29]) designed to identify and address students' misconceptions, thereby promoting a deeper understanding of the concepts. During the unit review, students were presented with Fig. 1 and guided to solve problems using the work-energy theorem. These instructional modifications aimed to help students develop a more integrated conceptual framework, similar to the one depicted by the solid lines in Fig. 1.

3. Design 3: Conceptual-framework-based cooperative learning instruction

The third instructional design incorporated the same instruction sequence, content, classroom examples, and homework as those used in design 2. The difference was that teaching method of design 3 adopted the cooperative learning instructional method. As detailed in Supplemental Material [29], questions marked with an "(Cooperative)" label were designed to be addressed using this approach during classroom instruction. This method promoted group discussions among students, aiming to deepen their learning experience.

To minimize alterations to the existing lecture-based instruction at the experimental school, and given that the instructional intervention spanned a month and covered an entire unit, informal cooperative learning, as proposed by the Johnson and Johnson [30], was considered a suitable

approach and adopted in design 3. This method was typically integrated with lecture-based instruction, incorporating brief, intermittent discussions multiple times during a lesson without requiring significant changes to traditional teaching methods.

The implementation of informal cooperative learning groups was guided by two fundamental principles: first, the clarity and precision of tasks and instructions; and second, the generation of tangible outcomes, such as written responses. The procedure began with a concise, targeted discussion that led to the formation of small groups comprising 2–4 students. The teacher then delivered the first segment of instruction, lasting approximately 10–15 min, during which atypical context questions were introduced. Students proceed to their first round of paired discussions, where they explored the teacher’s questions collaboratively.

Within these informal cooperative learning groups, the discussion progressed through several stages: (1) each student independently formulated and expressed their initial response; (2) students exchanged their ideas with peers; and (3) the group synthesized a collective answer that often surpasses the quality of individual initial responses through mutual consultation and consideration of diverse perspectives. To ensure equal participation, one student was randomly selected and given approximately 30 s to summarize their group discussion and answer to the class. This random selection motivated all group members to engage actively.

Following this, the teacher randomly selected a student to present the group’s discussion process and outcomes to the class. The teacher then delivered the second part of the lecture, after which students engaged in a second paired discussion. This cycle continued until the lecture concluded, ending with a summarizing discussion to integrate the learned content. This process was designed to stimulate active student participation and in-depth thinking while fostering both individual accountability and group cooperation.

In this instructional design, each lesson incorporated group-based collaborative learning, with seven atypical context questions distributed throughout the unit to support cooperative learning activities. Since the experiment “exploration of the work-energy theorem” naturally involved group cooperative learning, no additional atypical context questions were included for this lesson. Finally, during the unit review, Fig. 1 was presented to guide students in solving problems using the work-energy theorem.

C. Experimental procedure

1. Participant introduction

A mid-ranking high school located in an eastern coastal city of China was selected as the experimental site. Through the recruitment process, eleven parallel first-year high school classes (10th grade), comprising 517 students, were included in the study. Physics instruction was delivered by three

teachers: teacher A taught three classes, while teachers B and C each taught four classes.

This study employed a quasiexperimental design, where differences among teachers could not be fully controlled due to practical constraints. However, efforts were made to improve the equivalence in the teachers’ educational backgrounds and teaching experiences. All three teachers graduated from the same university with a master’s degree in physics education, where they received rigorous training in both physics content knowledge and pedagogical skills. Teacher A had six years of teaching experience, while teachers B and C each had five years of experience. Although there were slight variations in their individual teaching styles, administrative evaluations of their instructional skills, as well as the results of common physics examinations from their classes over the past three years, revealed minimal differences in teaching effectiveness. These findings indicate that the three teachers had comparable teaching abilities.

To align with an agreement with the high school to enhance student engagement in their physics course, more classes were assigned in the intervention group. In total, two classes ($N = 83$) were assigned as the control group (instructional design 1), four classes ($N = 188$) were designated as intervention group 1 (instructional design 2), and the remaining five classes ($N = 246$) were designated as intervention group 2 (instructional design 3). The student distributions of these experimental groups are shown in Table I.

All participants in this study were introduced to the basic qualitative ideas of work, mechanical energy, and energy transformation in approximately five class periods during their middle school physics curriculum in eighth grade. For example, in the study of kinetic energy, the textbook defines it as the energy of an object due to its motion. Through experiments, students explored the factors affecting kinetic energy, concluding that for objects of the same mass, greater velocity results in greater kinetic energy, and for objects moving at the same velocity, greater mass results in greater kinetic energy. However, the textbook did not introduce a specific formula for calculating kinetic energy [31]. In the first year of high school, students were required to review and deepen their understanding of these concepts,

TABLE I. Allocation of participants to experimental groups. Each checkmark (“✓”) in the table represents a class, with the number in parentheses indicating the number of students in that class.

Teacher	Control group (design 1)	Intervention group 1 (design 2)	Intervention group 2 (design 3)
Teacher A		✓ (49)	✓ (47), ✓ (52)
Teacher B	✓ (42)	✓ (49), ✓ (42)	✓ (48)
Teacher C	✓ (41)	✓ (48)	✓ (50), ✓ (49)

focusing on comprehending the interrelationship between work and mechanical energy from both the qualitative and quantitative perspectives. Additionally, the students were introduced to the work-energy theorem for the first time.

2. Instructional intervention plan

During the week prior to teaching the chapter on the work and mechanical energy, a pretest assessing physics knowledge integration was administered to all participating students using the work and mechanical energy test (WMET), which was developed in our previous research [22]. Since the students had developed some qualitative understanding of work and mechanical energy during their middle school physics courses, they were able to read and solve some problems during the pretest.

After the pretest, no intervention was applied to the control group, which followed the existing traditional instruction. In contrast, the intervention groups followed the conceptual framework-based instructional designs, with intervention group 1 using a lecture format and intervention

group 2 using a cooperative learning format. The specific instructional procedures for both the control and intervention groups are outlined in Table II. Finally, during the week after completing the unit on the work and mechanical energy, the same test was administered to all students as a post-test.

As shown in Table II, the instructional approaches for the intervention groups differ significantly from that of the control group in terms of sequence, content, and focus. For the instructional sequence, the intervention groups introduced kinetic energy and the work-energy theorem before gravitational and elastic potential energy. Regarding the content, the intervention groups replaced the experiment on verifying the principle of conservation of mechanical energy with an experiment on exploring the work-energy theorem, and the new experiment was moved before the introduction of potential energy, which allows a more in-depth discussion to connect the work-energy theorem with the concept of potential energy. The focus of the intervention groups consistently emphasizes the connections between potential energy, the principle of conservation of

TABLE II. Specific instructional procedures for the control and intervention groups.

Order	Control group	Intervention group 1	Intervention group 2
1	Introduction to the concepts of work and power	Introduction to the concepts of work and power (with five atypical context questions added)	Introduction to the concepts of work and power using cooperative learning approach (with five atypical context questions added, one of which is for cooperative learning)
2	Introduction to the concept of gravitational potential energy	Introduction to kinetic energy and the work-energy theorem (with seven atypical context questions added)	Introduction to kinetic energy and the work-energy theorem using cooperative learning approach (with seven atypical context questions added, two of which are for cooperative learning)
3	Introduction to kinetic energy and the work-energy theorem	Experiment: exploration of the work-energy theorem	Experiment: exploration of the work-energy theorem
4	Introduction to the principle of conservation of mechanical energy	Introduction to the concepts of gravitational and elastic potential energy, emphasizing their relationship with the work-energy theorem (with four atypical context questions added)	Introduction to the concepts of gravitational and elastic potential energy using cooperative learning instruction, emphasizing their relationship with the work-energy theorem (with four atypical context questions added, two of which are for cooperative learning)
5	Experiment: verification of the principle of conservation of mechanical energy	Introduction to the principle of conservation of mechanical energy, emphasizing its relationship with the work-energy theorem (with three atypical context questions added)	Introduction to the principle of conservation of mechanical energy using cooperative learning instruction, emphasizing its relationship with the work-energy theorem (with three atypical context questions added, two of which are for cooperative learning)
6	Review: presentation of a concept map	Review: presentation of a conceptual framework, guiding students to solve problems using the work-energy theorem	Review: presentation of a conceptual framework, guiding students to solve problems using the work-energy theorem

mechanical energy, and the work-energy theorem. Particular attention was given to the central role of the work-energy theorem, which was reinforced through atypical context questions designed to address misconceptions and deepen students' conceptual understanding. This was further supported by the cooperative learning method in design 3.

In the high school physics curriculum at the experimental school, simple concepts are typically taught over two class periods (45 min each). The first class focuses on explaining the concepts, principles, and examples, while the second class is dedicated to exercises and consolidation. For more complex concepts, the instruction typically spans three class periods, with one class devoted to explaining the concepts, principles, and examples, and two additional classes allocated to problem-solving exercises and knowledge consolidation. For experiments, instruction usually consists of two class periods, one for hands-on operation and the other for analyzing experimental results and discussing related exercises.

In the unit of work and mechanical energy, work, power, gravitational potential energy, and elastic potential energy were considered as relatively simple concepts and were each taught over two class periods, for a total of eight class periods. Kinetic energy and the work-energy theorem, along with the principle of conservation of mechanical energy, were considered as more complex topics and were allocated with three class periods each, totaling six class periods. The experiments on the work-energy theorem and the principle of conservation of mechanical energy each required two class periods. Additionally, after completing the unit, teachers typically dedicated four class periods to reviewing the content and problem solving for knowledge consolidation. Therefore, both the control group and the intervention group allocated 20 class periods to the work and mechanical energy unit. Since the first-year high school students at this school have four physics class periods per week, the instructional task of 20 class periods requires about five weeks to complete. Therefore, this quasiexperimental study was conducted over a period of a little over one month.

3. The key features of the instruction

The content and sequences of the instructional designs. Compared to the control group, the intervention groups not only adjusted the sequence of related knowledge instruction but also replaced the energy conservation experiment with an experiment on work-energy theorem to emphasize its central role in the conceptual framework. Furthermore, the intervention groups placed greater emphasis on the connections between the central idea and other concepts and principles throughout the instructional process. These changes were particularly reflected in the instruction of gravitational potential energy, elastic potential energy, and the principle of conservation of mechanical energy.

In the traditional instruction of the control group, the topic of gravitational and elastic potential energy was introduced before kinetic energy and the work-energy theorem, leading to a disconnect in the conceptual development between the potential energy and the work-energy theorem. In contrast, the intervention groups taught kinetic energy and the work-energy theorem first, creating an opportunity to establish a connection between them. During instruction on gravitational and elastic potential energy, the intervention groups not only explained the work done by gravity and elastic forces, the expression for gravitational potential energy, and its changes, but also discussed the relationship between the work done by these forces and the change in kinetic energy. For instance, students explored questions such as, "Why is throwing objects from high-rise building strictly prohibited? Explain from a physics perspective" or "What is the purpose of the arresting cables on the deck of an aircraft carrier? Explain using work and energy concepts." These example problems encouraged students to connect the work done by gravity and elastic forces with changes in potential energy and kinetic energy, integrating these concepts into the application of the work-energy theorem.

In the instruction on deriving the conservation principle of mechanical energy, the control group followed the textbook's approach of "inductive reasoning." This approach uses the mutual transformation of kinetic energy and gravitational potential energy as an example, focusing on a system where only gravity does work. Based on the work-energy theorem, it is derived that when kinetic energy and gravitational potential energy transform into each other, the total mechanical energy remains constant. Similarly, it is concluded that in a system where only elastic forces do work, the transformation between kinetic energy and elastic potential energy also maintains the constancy of total mechanical energy. Finally, it is generalized that in a system where only gravity or elastic forces do work, kinetic and potential energy transform into each other, and the total mechanical energy remains constant. This conclusion is defined as the principle of conservation of mechanical energy [28].

While the reasonableness and completeness of this inductive reasoning approach are not in question, the work-energy theorem plays only a marginal role throughout the derivation process. It becomes overshadowed and fails to establish a strong connection with the principle of conservation of mechanical energy. Moreover, the condition "in a system where only gravity or elastic forces do work" is ambiguously expressed. In fact, even in a system where both gravity and elastic forces act, the total mechanical energy of the system remains conserved.

In contrast, the intervention groups derived the principle of conservation of mechanical energy using a "deductive reasoning" approach. First, starting with the work-energy theorem: $W = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$, and considering a system

where only conservative forces do work (i.e., only gravity and/or elastic forces do work in this high school level mechanics course), the left-hand side of the equation represents the change in potential energy. Substituting for gravitational and elastic potential energy, this becomes: $mgh_1 - mgh_2 + \frac{1}{2}k\Delta l_1^2 - \frac{1}{2}k\Delta l_2^2 = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$. Rearranging terms yields: $mgh_1 + \frac{1}{2}k\Delta l_1^2 + \frac{1}{2}mv_1^2 = mgh_2 + \frac{1}{2}k\Delta l_2^2 + \frac{1}{2}mv_2^2$. This equation defines the principle of conservation of mechanical energy: in a system where only conservative forces do work, the total mechanical energy remains constant. This deductive reasoning approach not only provides a complete derivation but also emphasizes the close relationship between the work-energy theorem and the principle of conservation of mechanical energy, showing that the latter is a direct result of the former in the context that only conservative forces do work.

Problem-solving example. As discussed earlier, in teachers' discussions of example problems and students' homework, the control group did not emphasize the application of the central idea, the work-energy theorem. In contrast, the intervention groups highlighted the critical role of the work-energy theorem in the problem-solving process. As shown in Fig. 3, example 1 is a homework question assigned to the students in all groups.

This question can be solved using either the kinematics method or the recently introduced energy method based on the relationship between work and mechanical energy. An analysis of students' responses revealed that 59.42% of the students chose the kinematics method, 39.13% applied the energy method, and a small percentage did not provide an answer. In addressing this question, teachers in the control group used the kinematics method, whereas teachers in the intervention groups emphasized the application of the work-energy theorem and solved it using the energy method.

As shown in the figure below, a block with a mass of 1600 kg and an initial velocity moves upward a slope that makes a 6° angle with the horizontal. After moving for a while, the block reaches point A on the slope and continues to slide up for 4 m before it stops at point B. It is known that the kinetic friction coefficient between the block and the slope is 0.7, and the size of the block is ignored.

What is the speed of the block at point A?

($\cos 6^\circ \approx 1$, $\sin 6^\circ \approx 0.1$.)

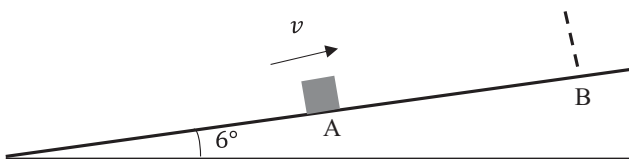


FIG. 3. Example 1 of the problem-solving practices.

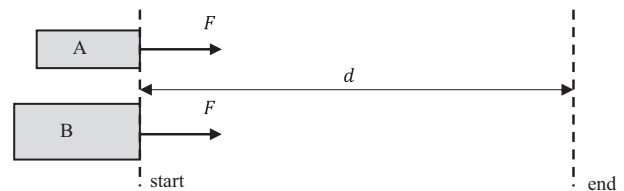
Example of cooperative learning instruction. In addressing atypical context questions, intervention group 2 implemented a cooperative learning method that emphasized group collaboration. In teaching kinetic energy and the work-energy theorem, an atypical context question was used in the instruction. Both intervention group 1 and intervention group 2 were presented with example 2 shown in Fig. 4. (Also see question 3 in Sec. 2: kinetic energy and the work-energy theorem of Supplemental Material [29]).

In intervention group 1, the teacher presented the question on a slide and allowed students 3–5 min for independent thinking and problem solving, followed by a direct explanation. In contrast, in intervention group 2, the teacher presented the question and asked students to form groups of 2–4 with their desk mates or nearby classmates. Each student first reflected independently for 1 min, after which group members discussed the question collaboratively for 2–4 min. Finally, the teacher randomly selected 1–2 groups to summarize their discussion and provided feedback to deepen their understanding. Below is an example of the discussion process from one group (consisting of three members) in intervention group 2, along with the teacher's feedback.

Student A: My initial thought was that the answer is B, as the block with less mass would experience greater acceleration. According to Newton's second law, the block with smaller mass would reach a higher velocity.

Student B: Yes, I thought the same. According to $v^2 = 2ad$, the acceleration of block A is $a_A = \frac{F}{m_A}$,

Two blocks with unequal masses ($m_A < m_B$) are initially at rest on a frictionless horizontal plane. A constant force F is applied to each block at the same starting line. The two blocks move from rest and travel the same distance d along the straight line as shown in the figure below. Which of the following statements correctly compares the kinetic energy of the two blocks at the end line? $m_A < m_B$



- The kinetic energies of both blocks are equal.
- The block with the smaller mass has greater kinetic energy.
- The block with the larger mass has greater kinetic energy.
- There is not enough information; the actual masses of the blocks are needed to compare kinetic energies.
- There is not enough information; the actual magnitude of the force F is needed to compare kinetic energies.

FIG. 4. Example 2 of the problem-solving practices.

so $v_A^2 = 2 \frac{F}{m_A} d$. Similarly, the acceleration of block B is $a_B = \frac{F}{m_B}$, so $v_B^2 = 2 \frac{F}{m_B} d$. From these equations, it appears that the square of the velocity of the smaller mass, block A, should indeed be greater than that of the larger mass, block B.

Student C: But that's just velocity, not kinetic energy. We need to consider the kinetic energy formula, $\frac{1}{2}mv^2$. Substituting the square of the velocity into the kinetic energy formula, for block A, the kinetic energy is $\frac{1}{2}m_A(2\frac{F}{m_A}d)$, which simplifies to Fd . Similarly, for block B, the derived kinetic energy is also Fd .

Student A: Oh, it seems our initial thought was incomplete. The kinetic energies of the two blocks are actually equal.

Student B: Indeed, we initially focused only on velocity, but both velocity and mass together determine the kinetic energy.

Student C: Let's consider the work-energy theorem, which states that the work done on an object equals the change in its kinetic energy. Since both blocks are subjected to the same force and move the same distance, the work done on them is the same. Consequently, the change in kinetic energy for both blocks is also the same.

Student A: So, the correct answer is A, both blocks have equal kinetic energy.

Student B: It seems we were off-track initially, but now we've arrived at the correct conclusion.

Student C: Yes, the answer is indeed A.

Teacher: This group initially focused only on velocity, which was a one-sided and incomplete approach. They then applied kinematics knowledge to arrive at the correct answer, but this process was unnecessarily complex. Finally, through further discussion, they opted to use the work-energy theorem, which allowed them to verify their answer accurately and efficiently. Moving forward, for questions involving work and kinetic energy, it may be beneficial to prioritize the work-energy theorem as the primary solving method, as it can help avoid unnecessary detours.

D. Assessment instrument

Based on our previous study of students' learning behaviors using the conceptual framework of work and mechanical energy, we developed and validated the work and mechanical energy test (WMET), a multiple-choice instrument designed to assess students' levels of knowledge integration. In the present study, this instrument was used to evaluate the effectiveness of different instructional strategies. The WMET consists of 20 questions distributed

TABLE III. Design features of the WMET. Based on the distribution of the context and concept features, it can be suggested that the traditional instruction seems to have more examples on work and conservation of mechanical energy, which show more typical questions. On the other hand, the work-energy theorem is somewhat less popular, and the related questions are often atypical to students.

Concept type	Context type	Questions
Work	Typical	Q1, Q2, Q3, Q4, Q5, Q7, Q12
CME	Typical	Q9, Q11, Q14, Q15, Q18
	Atypical	Q6, Q13, Q20
WET	Atypical	Q8, Q10, Q16, Q17, Q19

across three conceptual categories: work (7 questions), conservation of mechanical energy (CME) (8 questions), and the work-energy theorem (WET) (5 questions). The assessment incorporates both typical and atypical questions. Typical questions include those that are commonly used in instruction as examples or homework problems. Atypical questions, on the other hand, are designed to engage the central idea and often make use of unfamiliar contexts that students rarely encounter within the traditional curriculum. The definitions and classifications of typical questions and atypical questions are operational and straightforward; for physics teachers, the classification should be obvious from reading the questions. A detailed summary of the test's design features is provided in Table III [22].

The questions in the WMET are mostly adapted or modified from existing instruments including the Energy Concept Inventory [32], the Energy Concept Assessment [33], the Energy and Momentum Concept Survey [34,35], and several Chinese physics college entrance examination questions. A benefit of using existing questions is that the test questions can establish a basic level of validity and reliability. Although most questions were designed in prior studies for assessment of various features of student conceptual understanding of work and mechanical energy, the selective use and modification of these questions in this study are guided based on the conceptual framework for assessment of knowledge integration, which aims for a research goal different from those of the previous studies. Therefore, the assessment design in this study is not a repetition of the previous work but can provide new insights into students' learning from the perspective of knowledge integration.

III. RESULTS

For more valid comparisons, data from participants who missed either the pre- or the post-test or provided incomplete responses were excluded. Specifically, three participants were excluded from the control group, five from intervention group 1, and seven from intervention group 2.

TABLE IV. One-way ANOVA comparing pretest scores across the control and intervention groups for work and mechanical energy.

Concept domain	Source	Sum of squares	<i>df</i>	Mean square	<i>F</i>	<i>p</i>
Overall	Between groups	453.08	2	226.54	0.95	0.388
	Within groups	119034.97	499	238.55		
	Total	119488.05	501			
Work	Between groups	1100.32	2	550.16	1.12	0.327
	Within groups	244924.56	499	490.83		
	Total	246024.88	501			
CME	Between groups	1032.66	2	516.33	1.82	0.164
	Within groups	141975.62	499	284.52		
	Total	143008.28	501			
WET	Between groups	718.67	2	359.34	0.58	0.562
	Within groups	310982.53	499	623.21		
	Total	311701.20	501			

This data conditioning resulted in 80 participants in the control group, 183 in intervention group 1, and 239 in intervention group 2. In total, data from 502 students (268 males and 234 females) were considered valid and used in the analysis.

the current experimental conditions, the pretest performances of the three groups in work and mechanical energy did not exhibit significant differences. Therefore, the three groups can be considered as representing a single homogeneous population.

A. Pretest results

A one-way ANOVA was conducted to compare the pretest scores of the intervention and control groups to evaluate their homogeneity prior to instruction (see Table IV). The results indicated that the overall pretest scores showed no significant differences between groups ($F = 0.950$, $p = 0.388 > 0.05$). Similarly, the between-group differences for the three individual indicators (“Work,” “CME,” and “WET”) were not statistically significant ($p > 0.05$). These findings suggest that, under

B. Effectiveness of the instructional intervention

Although the control and intervention groups demonstrated similar performances on the pretest, their post-test results revealed significant differences, as shown in Fig. 5 and Table V. To evaluate the effectiveness of different instructional strategies, a t test was conducted to compare the score changes from pretest to post-test among the groups: intervention group 1 (I1) and the control group (C), intervention group 2 (I2) and intervention group 1 (I1), and intervention group 2 (I2) and the control group (C).

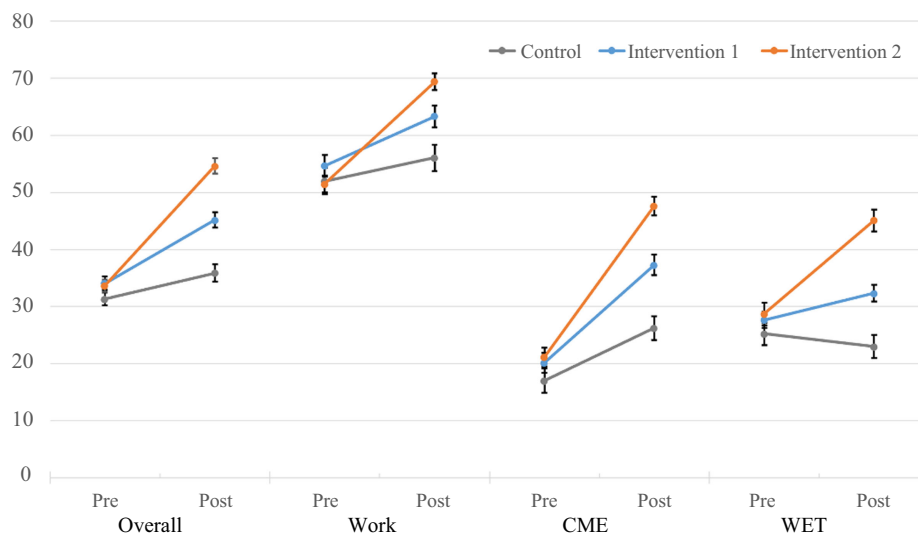


FIG. 5. Pre-post scores of the WMET and concept dimensions.

TABLE V. Comparison of changes between post-test and pretest for each group.

Group	Concept domain	Post-test score (SE)	Pretest score (SE)	ΔS	t	p	d
Control	Overall	35.88 (1.49)	31.31 (1.11)	4.56	2.99	0.004	0.39
	Work	56.07 (2.33)	51.96 (1.92)	4.11	1.60	0.114	0.22
	CME	26.25 (2.10)	17.03 (1.45)	9.22	4.26	<0.001	0.57
	WET	23.00 (1.98)	25.25 (2.70)	-2.25	-0.88	0.383	-0.11
Intervention 1	Overall	45.16 (1.72)	34.10 (1.18)	11.07	7.83	<0.001	0.64
	Work	63.31 (1.89)	54.64 (1.72)	8.67	3.88	<0.001	0.35
	CME	37.30 (1.78)	20.15 (1.17)	17.14	9.15	<0.001	0.84
	WET	32.35 (1.43)	27.65 (1.95)	4.70	2.48	0.014	0.20
Intervention 2	Overall	54.62 (1.38)	33.66 (1.07)	14.74	17.37	<0.001	1.10
	Work	69.40 (1.48)	51.46 (1.47)	12.35	10.58	<0.001	0.79
	CME	47.65 (1.63)	21.18 (1.21)	20.32	16.21	<0.001	1.19
	WET	45.10 (1.93)	28.70 (1.56)	9.16	8.58	<0.001	0.61

The results were as follows: $t(I1, C) = 3.13$, $p = 0.002$, $d = 0.39$; $t(I2, I1) = 5.34$, $p < 0.001$, $d = 0.52$; $t(I2, C) = 8.43$, $p < 0.001$, $d = 1.00$. These findings indicate that the instructional strategy emphasizing the central idea is more effective at enhancing students' deep understanding and knowledge integration than the traditional instruction. Additionally, the cooperative learning instruction used in intervention group 2 further improved students' knowledge integration, with a moderate to large effect sizes based on Cohen's d [32,36].

A comparison of pretest and post-test results revealed varying degrees of improvement across the assessed domains. The results showed that, overall, the effect size was largest in intervention group 2 [$t(239) = 17.37$, $p < 0.001$, $d = 1.10$], followed by intervention group 1 [$t(183) = 7.83$, $p < 0.001$, $d = 0.64$], and the control group [$t(80) = 2.99$, $p = 0.004$, $d = 0.39$]. For specific domains, the most substantial gains were observed in the CME dimension, where all groups demonstrated notable progress; however, the intervention groups exhibited significantly greater improvement compared to the control group. In the work dimension, all groups showed smaller growth rates relative to the CME dimension, though the intervention groups maintained a clear advantage. Finally, in the WET dimension, a significant divergence was observed between the groups: intervention group 2 achieved a medium positive gain [$t(239) = 8.58$, $p < 0.001$, $d = 0.61$], intervention group 1 achieved a small positive gain [$t(183) = 2.48$, $p = 0.014$, $d = 0.20$], while the control group showed a minor decline in performance [$t(80) = -0.88$, $p = 0.383$, $d = -0.11$]. These findings underscore the effectiveness of the modified interventions in enhancing students' knowledge integration.

To more precisely illustrate the impact of different instructional strategies on changes in students' knowledge integration levels, a knowledge integration level transition diagram was created, as shown in Fig. 6. In this diagram, the percentages in the box under novice, intermediate, and

expert indicate the proportion of students at each level. Students' knowledge integration levels were categorized based on total score ranges of 0–40–80–100, corresponding to novice, intermediate, and expert levels as defined in a previous study [22]. Arrows indicate the direction of transitions between levels, with the fractions above these arrows representing the proportion of students making these transitions. To facilitate observation, arrows were assigned different colors based on the pretest levels of the students: green for novice, blue for intermediate, and red for expert. This graphical representation provides critical insights into how different instructional strategies influence students' progression across knowledge integration levels.

The diagram reveals that in the control group, transitions occurred only between the novice and intermediate levels. A small fraction of novice students (0.25, SE = 0.04) advanced to the intermediate level, while a significant portion of intermediate students (0.47, SE = 0.13) regressed to the novice level, indicating a negative transition. By comparison, intervention group 1 exhibited transitions not only between novice and intermediate levels but also between intermediate and expert levels. When compared to the control group, the proportion of novices advancing to the intermediate level increased to 0.44 (SE = 0.04), while the fraction of intermediate students regressing to the novice level decreased to 0.19 (SE = 0.06). Additionally, a small fraction of intermediate students (0.04, SE = 0.03) progressed to the expert level. Meanwhile, intervention group 2 demonstrated transitions across the entire spectrum. The proportion of novices advancing to the intermediate level further increased to 0.60 (SE = 0.04), and a small fraction (0.05, SE = 0.02) made a "long-range" transition going directly from the novice level to the expert level. The negative transition of intermediates regressing to novices dropped significantly to 0.06 (SE = 0.03), while the proportion advancing to the expert level increased to 0.38 (SE = 0.07). However, one student initially at the expert level regressed to the

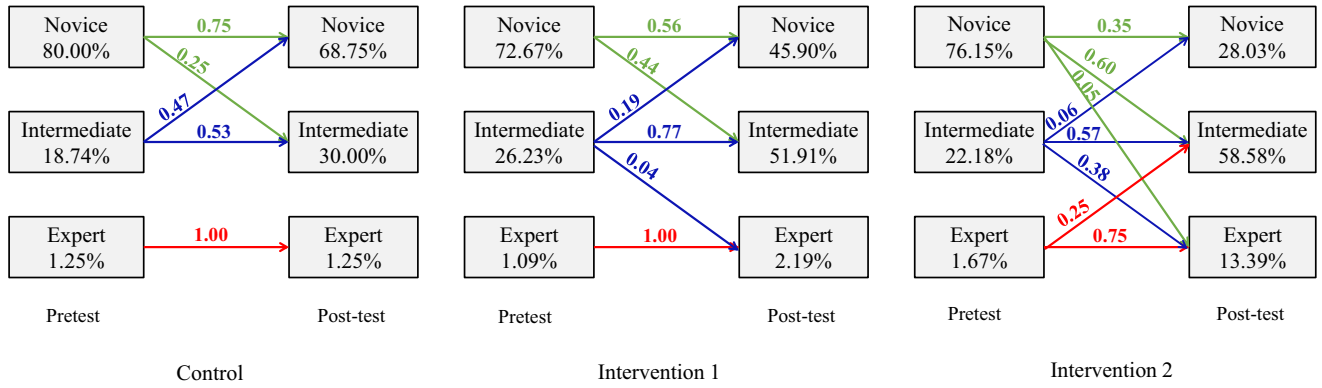


FIG. 6. Knowledge integration level transition diagram.

intermediate level. Discussions with teachers revealed that this student, who was previously recognized for excellent grades, had recently shown signs of complacency and a lack of challenge. This shift in mindset might have negatively impacted the student's learning attitude and effort, leading to declines in performance across multiple subjects.

The analysis indicates that students' knowledge integration level transitions from pretest to post-test can be broadly classified into three categories: positive transition, where the post-test knowledge integration level is higher than the pretest level; negative transition, where the post-test level is lower than the pretest level; and no transition, where the post-test level remains unchanged. The distribution of knowledge integration level transitions for each group is summarized in Table VI.

Conceptual-framework-based instruction, as implemented in intervention group 1, was found to facilitate greater positive transitions in students' knowledge integration levels (32.79%) compared to traditional instruction in the control group (20.00%). Furthermore, conceptual-framework-based instruction integrated with a cooperative learning method, as implemented in intervention group 2, had an even greater impact, with 57.74% of students demonstrating positive transitions in knowledge integration. These findings confirm the effectiveness of instructional strategies that focus on the central idea, as well as those that integrate cooperative learning with the central idea, in fostering students' knowledge integration.

TABLE VI. Proportional distribution of knowledge integration level transition directions across different groups.

Group	Positive transition	Negative transition	No transition
Control	16 (20.00%)	7 (8.75%)	57 (71.25%)
Intervention 1	60 (32.79%)	9 (4.92%)	114 (62.30%)
Intervention 2	138 (57.74%)	4 (1.67%)	97 (40.59%)

IV. CONCLUSION

In our previous study, we developed a conceptual framework for work and mechanical energy and designed an assessment tool to evaluate students' knowledge integration in learning mechanical energy [22]. Building on the previous work, the present study focuses on implementing instructional strategies derived from the conceptual framework to promote deep learning. To measure the effectiveness of these strategies, the associated assessment tool was employed. Specifically, the modified instructions, guided by the conceptual framework, emphasized understanding the central idea, the work-energy theorem, and its connections to other knowledge elements, thereby helping students achieve more comprehensive knowledge integration. Furthermore, this study incorporated a cooperative learning method into the conceptual-framework-based instruction, which has demonstrated effectiveness in further enhancing students' knowledge integration.

A comparison of the pretest and post-test results of knowledge integration between intervention group 1 and the control group revealed that instructional strategies emphasizing the central idea significantly enhanced students' knowledge integration levels compared to traditional instruction ($p = 0.002$, $d = 0.39$). Furthermore, a comparison between intervention group 2 and intervention group 1 showed that the classes which emphasized the central idea and incorporated cooperative learning instruction achieved a significantly greater improvement in knowledge integration than the class focusing solely on the central idea ($p < 0.001$, $d = 0.52$). These findings demonstrate that instructional strategies emphasizing the central idea and integrating cooperative learning can both contribute to improving students' knowledge integration, and the combination of the two strategies can produce the most pronounced effects ($p < 0.001$, $d = 1.00$). This insight provides valuable perspectives for developing instructional methods for promoting knowledge integration.

Although this study yielded encouraging outcomes, several limitations should be acknowledged. First, the control and intervention groups were taught by different

teachers, which is a common constraint in real-world classroom studies. Future research could include a broader range of teachers to better account for variability in teaching styles and instructional approaches. Additionally, in intervention group 2, cooperative learning instruction was applied to only some of the atypical questions in each lesson, with cooperative learning embedded within a lecture format. Whether extending this approach to all atypical questions or implementing a fully cooperative learning instructional model would lead to greater improvements in knowledge integration remains an open question for future research. Finally, the design choices in this study were shaped by the constraints of China's national physics curriculum standards, which designate mechanical energy and the work-energy theorem as central learning goals at the high school level. As such, our instructional design and assessment tools were aligned with the official curriculum, with the primary goal of exploring how knowledge integration could be enhanced within this established framework. While this focus allowed us to demonstrate the effectiveness of conceptual framework-based instruction in improving student reasoning within the defined scope, it does not address the broader conceptual development of energy across different forms and contexts. Specifically, as highlighted in prior work by Arons [37], Sherwood [38], Sherwood and Bernard [39], and Jewett [40–44], mechanical energy is not conserved in all physical processes, and it represents only a subset of the total energy framework articulated by the first law of thermodynamics. The conservation of mechanical energy, though mathematically tractable and commonly featured in high school physics curricula, does not adequately prepare students to reason about energy dissipation, thermal energy, or internal energy transformation. These gaps can hinder students' ability to

develop a robust and transferable understanding of energy concepts. Future research and curriculum development efforts should consider how to scaffold students' conceptual progression from mechanical energy toward more general representations of energy conservation that are compatible with the first law of thermodynamics.

In conclusion, this study builds upon and enriches previous work on the conceptual framework of work and mechanical energy. Consistent with earlier studies on knowledge integration interventions [16,19–21,25,45], this study provides further evidence supporting the value of the conceptual framework model in guiding instruction. Additionally, it demonstrates that incorporating a cooperative learning method contributes to more substantial improvements in students' knowledge integration, thereby enriching instructional strategies for promoting deep learning.

ACKNOWLEDGMENTS

The authors would like to acknowledge the help of the Editor and anonymous reviewers. The research is supported by the National Natural Science Foundation of China (No. 42405135).

Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies.

DATA AVAILABILITY

The data supporting this study's findings are available within the article.

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