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Effectiveness of conceptual-framework-based instruction on promoting knowledge integration in learning simple electric circuit

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Student learning in simple electric circuits has been an important area in physics education research. This study builds off a previous investigation that applied the conceptual framework model to examine knowledge integration in student learning of simple electric circuits and developed a multiple-choice concept test for assessing knowledge integration in simple electric circuits. In this study, a conceptual-framework-based teaching intervention was developed and implemented in a controlled study with high school students in China to evaluate the effectiveness of the new instruction. Using the instrument developed in the previous study, a pretest, a post-test, and a delayed post-test were conducted with both groups of students. The delayed post-test was included to further evaluate knowledge retention as evidence of knowledge integration. The results suggest that the conceptual-framework-based teaching intervention was effective in promoting knowledge integration compared to the existing instruction.

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I. INTRODUCTION

Improving students' conceptual understanding has been a central goal of physics education [1–6]. Research has shown that many students still lack a deep understanding of basic physics concepts after traditional instruction [7–9]. Traditional instruction and problem-solving practices often result in students engaging in rote-based learning, using routine strategies and operations to manipulate equations without developing a deep understanding or reasoning skills [10–12]. For example, while students may develop routine strategies to solve familiar quantitative questions, they often encounter difficulties with conceptual and qualitative problems [10,11,13]. In addition, research has shown that after traditional high school physics instruction, students tend to rely on memorization-based strategies linked to familiar contexts taught in class [14–17]. As a result, many students still lack a deep understanding of the basic physics concepts after traditional instruction [7,8,18].

Over the years, teaching interventions have been proposed to address students' conceptual difficulties in learning electricity, yet with limited efficacy [12,19]. Misunderstandings such as the shared current model, clashing current model, short circuit misconception, power supply as a constant current source, and local reasoning are still prevalent among students in their learning of simple circuit concepts [20–24]. Ample research has been conducted on developing instructional interventions to improve students' understanding or change their misconceptions of specific concepts in electric circuits using methods such as analogies, conceptual change text (CCT), and computer simulations [25–28]. For example, Coruhlu *et al.* found that using different conceptual change strategies was meaningfully effective in eliminating students' alternative conceptions of "electricity resistance" and "electricity current" [28]. It has also been found that students who used simulation and conceptual change text (CCT) in teaching series circuits at the university level learned more than those who did not, but contrary to expectations, the use of simulation did not improve the effectiveness of CCT [29]. Despite extensive research efforts employing diverse instructional interventions aimed at improving students' conceptual grasp, longitudinal assessments of conceptual understanding within the context of simple electrical circuits persistently revealed a pattern of recurring and deeply ingrained misconceptions among learners [3,22,23]. Therefore, research into instructional interventions that aim to help students achieve a deeper understanding of concepts on electricity remains a vital area of study [3,22,30,31].

To promote deep conceptual understanding in teaching and learning, it is beneficial to model students' conceptual understandings through the knowledge integration perspective [32]. Linn observed that when students achieve a deep

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understanding of scientific concepts, their knowledge structures transition from a fragmented knowledge organization into a well-integrated knowledge system, where the process of organizing these fragmented pieces of information into more universally applicable principles is known as the knowledge integration process [33,34]. In recent studies, a conceptual framework model has been developed to specifically target aspects of knowledge integration of students' conceptual understandings in learning physics [15,17,35,36]. The conceptual framework model is a concrete instantiation of the generally defined knowledge integration perspective and provides an operating tool that can explicitly model the knowledge structures of students from novices to experts and guide the design of assessment that targets features and levels of students' knowledge integration.

In our previous study [36], we applied the theoretical framework of knowledge integration to evaluate students' conceptual understanding of simple electric circuits in terms of their levels of knowledge integration. For the assessment, we developed a conceptual framework model for simple electric circuits, depicted in Fig. 1, which will guide the development of teaching interventions in this study. The conceptual framework has a hierarchical structure anchored with a central idea, which establishes the foundational understanding of the concept: "The total charges in a neutral conductor are conserved with the carrier charges (free electrons) in a conductor in random motion. When forces are applied to the free electrons due to an electric field (E-field), the electrons can have a net directional motion that leads to the concept of current. Such motion is impeded by collisions with microscopic structures and particles in the conductor, which leads to the concept of resistance."

The conceptual framework delineates the cognitive pathways that novices and experts traverse through interconnected layers and directional arrows. It serves as a tool to guide the development of an assessment instrument of knowledge integration in students' learning [36], the Test of Knowledge Integration in Electric Circuits (TKIEC). TKIEC implements three measurement designs including link type for measuring knowledge connectivity, typical vs atypical contexts for measuring the influence of contextual saliency, and microscopic vs macroscopic models for probing the understanding of the central idea. Analysis of the assessment outcomes allows the categorization of participants into three distinct levels of knowledge integration: novice, intermediate, and expertlike [36]. These levels represent a developmental progression from superficial understanding to deep conceptual comprehension [36,37].

Research has shown that experts and novices have fundamental differences in their knowledge structures [38–42]. Expertlike learners are able to develop a comprehensive knowledge structure in which different knowledge components and connections are integrated around the central idea of a concept. In contrast, the knowledge structures of novice students are often fragmented with only local connections between context features and memorized problem-solving procedures [38–42]. The main

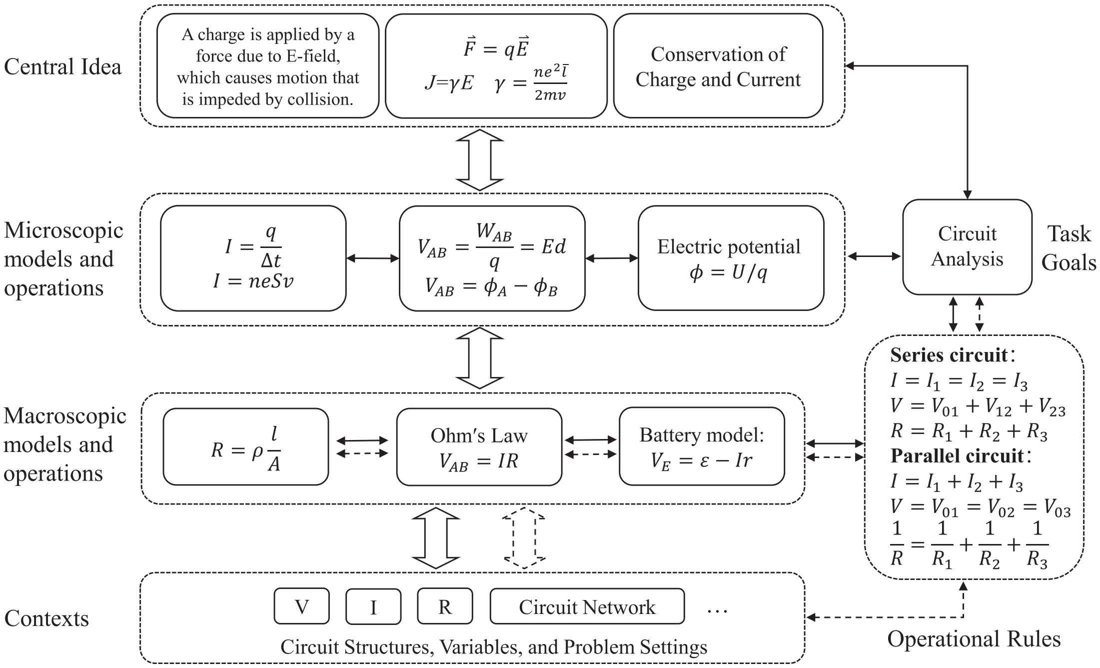

FIG. 1. The conceptual framework model of simple circuits developed in the previous study [36]. The solid arrows represent the conceptual pathways of experts, and the dashed arrows represent the conceptual pathways of novice students.

difference between an expert and a novice can be probed based on the extent to which one understands the central idea. The knowledge integration around the central idea is intentional and will promote deep learning for students [42]. In our previous work, the conceptual framework model has been developed as a method to study knowledge integration and deep learning in several recent studies on topics including light interference [14], force and motion [18], momentum [15], wave propagation [17], Newton's third law [16], work and mechanical energy [35], and measurement uncertainty [43]. The results have demonstrated the utility of the conceptual framework model in guiding assessment and instruction to promote knowledge integration in student learning.

This research builds off the previous study on student learning of simple electric circuits [36], which revealed that students' difficulties were the result of their lack of understanding of the central idea of simple electric circuits. Informed by the previous research, conceptual-framework-based instruction has been developed, which makes explicit emphasis on teaching the central idea and using specially designed demonstrations and practice examples to help students develop connections between the central idea and other knowledge elements. This study uses a controlled experiment with three measures including a pretest, a post-test, and a delayed post-test to evaluate the effectiveness of the conceptual-framework-based instruction, compared to the traditional instruction, on improving students' knowledge integration in learning simple electric circuits. Here, the delayed post-test was used as additional evidence to determine if the new instruction is effective in promoting knowledge integration and deep learning.

II. RESEARCH DESIGN AND METHODS

In the existing instruction, teachers in China are required to teach based on a standardized syllabus. Research has also shown that teachers in other education settings also traditionally base their instruction off their syllabus, and they tend to focus on topics routine numerical problem-solving practices without developing a deep conceptual understanding [31]. For example, when explaining the concept of current in high school physics in China, traditional lectures often ask students to recall the definition of current that students learned in middle school. Then new formulas for calculating current and related variables are introduced along with substantial problem-solving exercises. In this type of teaching, content is centered on how students should understand the applications of a definition or formula. As a result, students tend to view each topic separately instead of connecting them with other related knowledge [36]. In this type of learning, students often fail to develop a sufficient understanding of the central idea of the concept and its connections to other knowledge elements, which leads to fragmented knowledge structures. This study uses a newly developed conceptual-framework-based instruction to help students develop the central idea and strengthen the connections between the central idea and other components of students' knowledge structures to promote knowledge integration.

To evaluate the effectiveness of the instructional intervention, data from a pretest, a post-test, and a delayed post-test were collected from both the intervention and control groups. The control group used the existing traditional instruction while the intervention group used the conceptual-framework-based instruction, which will be discussed in detail next. The instrument developed in the previous research was used in all three tests [36]. Here, the delayed post-test was conducted to determine whether students showed significant signs of forgetting or not. Since the literature suggested that traditional instruction often promotes rote-based learning [44], the delayed post-test should then reveal further evidence of the effectiveness of the new instruction in helping students develop a deep conceptual understanding rather than memorization [36,45]. It is hypothesized that when comparing the scores on the post-test and delayed post-test, the intervention group will show fewer decreases in scores on the delayed post-test than the control group. In addition, it is also expected that score decreases on the delayed post-test will be less on questions requiring the understanding of the central idea than other questions that can be solved with memorization-based strategies. The details of the intervention designs and data collection are discussed next.

A. Design of the instructional intervention

The teaching intervention places emphasis on teaching the central idea and connecting it to other knowledge components, which was implemented in the intervention group. The control group was given the existing instructions. Both intervention and control classes used traditional-style lectures with the same example questions. In the intervention group, the instruction frequently guided students to discuss the central idea and connect it to other conceptual components to develop problem-solving strategies based on the central idea. In the control group, the instruction introduced the definitions of electric current and the related concepts and equations without emphasizing the central idea. Students were then guided to apply the given equations in problem-solving practices that were mostly computation questions.

In the intervention group, the teaching followed closely the conceptual framework model of the simple circuit developed in the previous study (see Fig. 1) [36]. The instruction first emphasized the central idea that charge is applied by a force in an electric field, which leads to motion that is impeded by collision. Based on the knowledge learned in the electrostatic field, the essence of circuit operation was analyzed from a microscopic perspective to provide students opportunities to systematically understand the principle of circuit operation from the microscopic perspective such as field and charges and the connections among voltage, field, and current. Then, the concept of conservation was introduced, including the conservation of electric charge and the conservation of current which completes the introduction of the central idea. After clarifying the nature of circuit operation based on the central idea, students were guided to learn the connections between the central idea and other knowledge elements in the simple electric circuit. Typical examples were then used to guide students to use the central idea to analyze and solve problems. This teaching strategy is designed to help students structure their knowledge around the central idea in order to promote knowledge integration and deep learning.

In this study, the teaching format of the intervention is lecture based, which is identical to the format of the compared traditional instruction. The difference is in the content, where the intervention places explicit emphasis on constructing the central idea of the conceptual framework and making connections between the central idea and the other components of students' knowledge structures. As a means of controlling variables, this intervention method focuses on change in content emphasis while keeping the existing instructional format unchanged, which is easier to implement in large lecture classes and allows a clear comparison to determine the instructional effectiveness of using conceptual-framework-based content in lecture-based instruction.

In both the intervention and control classes, the instruction followed the same sequence of topics in three steps, while the focus of the content differed. For example, in the first step, the traditional instruction in the control class began by asking students to revisit what they had learned in middle school. This was done using example questions similar to those they had encountered before, helping them recall prior knowledge and make connections to the new content. In contrast, the intervention class used the same type of examples but with a different purpose that aimed to motivate students' discussions for uncovering any misconceptions and developing the correct understanding based on the central idea. Detailed comparisons between intervention and traditional instruction are summarized below and listed in Table I:

1. Both instructions used similar physics examples and scenarios in the lesson. Traditional lecture instruction focused on whether students could recall the definition of the current they learned in middle school and apply the definition as a foundation for learning the new content. Within the traditional instruction, the teacher focused on helping students recall the previous definition before further explaining new content. If students were able to recall the definition, the teacher assumed that the students had a good conceptual understanding and proceeded with the lessons more quickly. However, this process was often ineffective in probing students' conceptual understanding and only determined whether students could still remember what they learned previously.
2. The intervention group also began by reviewing the definition of electric current. However, students would then engage in discussions on why and how an electric current is produced, which helped uncover their initial misconceptions.
3. For teaching the new content, the traditional instruction focused on introducing definitions and deriving mathematical formulas without discussing the concepts from microscopic models of how a circuit works. For example, teachers following the traditional curriculum often would not introduce the microscopic model of constant current generation.

TABLE I. Comparisons between intervention and traditional instructions.

Steps	Conceptual-framework-based instruction	Traditional instruction
1	Give problem scenarios to stimulate student thinking.	Review what students have learned. Introduce the new lesson teaching content.
	For example:	For example:
	The teacher introduces the following scenario: the amount of electricity passing through any cross-section of a conductor per unit time is called current. How is the current generated?	Teacher: Who can give the definition of electric current that we studied in middle school?.
	This process leads students to expose their own ideas.	Student: The amount of electricity passing through any cross-section of a conductor in unit time is called current.
	Teacher: Some guesses are voltage, some guesses are resistance, and some guesses are electric field, so what exactly is it? Today we are going to learn the microscopic operation principle of electric current and its application.	Teacher: Right! We will learn more about current today

(Table continued)

TABLE I. *(Continued)*

Steps	Conceptual-framework-based instruction	Traditional instruction
2	Lead students to initially establish the central idea through reasoning.	An operational definition.
	For example:	Teacher: This is the definition of constant current in high school: A current meter is connected in series in the circuit, and the current indicates a constant number. This current, whose magnitude and direction do not change with time, is called a steady current.
	Teacher: What is the difference between the motion of electrons in a conductor with or without a current passing through it?	Teacher: It should be noted that a constant current can only be constant if the magnitude and direction of the current do not change.
	Student: One is free and irregular motion, and the other is directed motion.	Teacher: The definition of current intensity is consistent with that of middle school, and students must remember its definition and formula.
	Teacher: Why do electrons move in directed motion to produce an electric current? You can make a guess by combining the knowledge of the electrostatic field. Student: The free electrons are subjected to electrostatic force. Teacher: How is the electrostatic force generated? Student: The electric field. Teacher: Why is there electric field? Student: There is an electric potential difference. Teacher: Let me summarize, in fact, free electrons always exist in the conductor. When there is a potential difference between the two ends of the conductor, there is electric field established inside the conductor, and the free electrons move directionally under the action of electrostatic force. (Point out the central idea and sort out the relationship between related concepts: electric potential difference → field → current microscopic model) Teacher: Okay, so based on the previous analysis, how should the macroscopic definition of steady current in the book be interpreted if we use a microscopic perspective? Student discussion Teacher: Under the action of a stable electric field, the free charges in the conductor create a directional motion and constantly collide with the stationary particles in the conductor in the process of moving. The collisions impede the directed motion of the free charges. The result is that the average rate of directed motion of all free charges does not change with time.	
3	Typical example training: In the practice questions, students are further guided to use the central idea to solve problems, rather than memorizing formulas to calculate answers. Practice problems are used as contextual support to guide students to review what they have learned and to strengthen the connection between the central idea and other knowledge components.	Typical example training: Practice questions require the use of microscopic formulas for calculation. Students are instructed to correctly find the corresponding value and calculate the magnitude of the current. Focus on students' proficiency in the application of formulas.

Instead, they had students memorize textbook definitions such as “A current meter is connected in series in the circuit, and the current indicates a constant number. This current, whose magnitude and direction do not change with time, is called a steady current.”

4. In contrast to traditional instruction, the conceptual-framework-based approach emphasizes teaching the central idea and gradually guiding students to learn all the components of the concept with clear connections to this central idea. Initially, the central idea was demonstrated, followed by an introduction to the microscopic model of constant current, which explained: “Under the action of a stable electric field, the free charges (electrons) in a conductor form a directional motion, which is impeded by collisions with microscopic structures and particles in the conductor. At equilibrium, the average rate of this directional motion of the free charges remains constant over time, forming a constant current.” After discussing the microscopic model, the macroscopic behavior was introduced, establishing that a constant current is observed when the magnitude and direction of the current remain unchanged when measured by an ammeter.
5. Another major difference in teaching between the intervention and control groups was in the interpretation process of typical practice questions. The intervention group prioritized in explicitly introducing the central idea and making connections to it for developing an integrated conceptual understanding. In contrast, the control group focused on extracting variables from problem scenarios and using textbook formulas to solve problems. Taking the after-school exercises from the textbook as an example, the differences in problem-solving methods between the two groups are further explained in Table I.

B. Data collection

The participants in this study were from two high school classes of similar level in a city in southern China. There were 42 students in the control class and 43 students in the intervention class. Both classes were taught by the same teacher, maintained the same instruction schedule, and were given the same practice problems throughout the experiment. The experiment started with a curriculum unit on simple circuits. At the time of the experiment, the students in both classes had finished their learning of electrostatic fields, which lays the knowledge base for understanding the central idea. Students also learned some basic knowledge about electric current in their middle school physics courses. The instruction on the simple electric circuit lasted for one and a half weeks including three lectures, three recitations, and one lab. The intervention group used the conceptual-framework-based instruction that made repeated emphasis on teaching the central idea and using it to explain and connect other knowledge components. Meanwhile, the control group was taught based on the topics sequentially off the textbook list.

C. Measurement design

In this study, three tests were conducted with the control and intervention classes including a pretest, a post-test, and a delayed post-test. The pretest was conducted before the instruction on the simple circuit. The post-test was conducted immediately after the teaching of the simple circuit unit was completed. The delayed post-test was conducted two weeks after the post-test was administered.

All three tests used the same instrument, the Test of Knowledge Integration in Electric Circuits (TKIEC), which was developed in the previous study [36] and contains 30 multiple-choice questions summarized in Table II. The test was designed to identify unique learning behaviors of students at different levels of knowledge integration, including context-dependence, fragmentation of knowledge, memorization-based problem solving, difficulty in transferring to novel contexts, and lack of meaningful connections between microscopic and macroscopic models of electric current [36].

The design of TKIEC utilizes a combination of typical and atypical questions to address the contextual salience of assessment questions. Typical questions are those that students frequently encounter in lectures, textbooks, and homework, which can often be solved using memorized equations and problem-solving procedures. In contrast, atypical questions are designed with unfamiliar contexts that necessitate the application of the central idea for correct resolution. The assessment design also incorporates knowledge connectedness, following the knowledge integration rubric developed by Linn *et al.* [32,46], which is

TABLE II. Question design for assessment of knowledge integration [36].

		Concept		
Link type	Context	Macroscopic model questions	Microscopic model questions	Number of questions
Single	Typical	1, 4, 5, 6, 10, 12, 13, 19, 22, 24	14	11
Multiple	Typical	9, 11	15, 28	4
Multiple	Atypical	2, 18, 26	3, 20, 21, 29	7
Integrated	Atypical	25	7, 8, 16, 17, 23, 27, 30	8

aligned with the link types in the structure of the observed learning outcomes (SOLO) taxonomy [47]. The original link types have been simplified into three types including single link, multilink, and integrated link [17]. Single-link problems require the establishment of a single connection between contextual features and operational rules, often solvable through memorization. Multilink problems demand connections between multiple conceptual components and operations, but these connections are typically locally linked without engaging the central idea. Integrated-link problems, however, require students to understand the central idea and construct an integrated knowledge structure based on the central idea. Furthermore, the conceptual framework of electric circuits, as depicted in Fig. 1, offers a unique perspective on knowledge integration by distinguishing between microscopic and macroscopic models. Microscopic models serve as the central idea's instantiation for explaining circuit operations at a fundamental level, providing an additional feature for assessing knowledge integration.

Empirical studies have demonstrated that the incorporation of a delayed post-test subsequent to an educational intervention can provide a more robust assessment of instructional efficacy [48–50]. Two common reasons for conducting delayed post-tests can be considered: (1) the delayed post-test can mitigate potential measurement artifacts of an immediate post-test due to short-term memorization strategies employed by learners; and (2) by addressing the short-term memorization issue, results from the delayed post-test can better discern whether participants have genuinely internalized the conceptual knowledge [51].

Therefore, in addition to the popular pre-post design seen in typical intervention studies, a delayed post-test was included in this study. It was designed to gather further evidence to evaluate whether students achieved a thorough understanding of the central idea, as opposed to mere memorization, indicative of knowledge integration and deep learning. For students who rely significantly on memorization-based learning and problem-solving methods, it is expected that their scores should reveal significant decay on the delayed post-test compared to the post-test due to forgetting and possible interference from new incoming materials in instruction. On the other hand, students who have achieved an integrated understanding based on the central idea should be able to reason with their understanding of the central idea to solve the problems without relying on memorization, and therefore, their scores on the delayed post-test are expected to have minimal decay from their post-test scores.

In addition, different designs of questions can also have varied outcomes on their score decays on the delayed post-test. For example, questions designed with typical contexts and or targeting macroscopic current models, which can be solved with memorization-based strategies, may have a large increase in the post-test scores compared to the pretest. However, it is also expected to see a significant decay in the delayed post-test scores due to the same reason of students using memorization-based approaches. In contrast, questions designed with atypical contexts and or targeting microscopic models require a good understanding of the central idea. The pre-post score gains on these questions are often smaller than those on single-link typical questions that can be solved with memorization-based strategies, but the score decay on the delayed post-test is expected to be less than that of the memory-based questions.

Furthermore, comparing the score decay on the delayed post-test between the control and intervention classes can provide additional evidence to show if the intervention can help more students achieve a good understanding of the central idea. If the intervention is effective, it is then expected that the score decay on the delayed post-test of the intervention class should be less than that of the control class.

III. RESULTS

A. Pretest data analysis

The pretest scores of the intervention and control group are listed in Table III, which show that the differences in the total scores and mean scores on different question types are not statistically significant ($p > 0.05$). The results suggest that students' level of understanding of simple electric circuits is similar for the two classes before high school instruction.

The results also reveal that students had developed some basic understanding on single-link questions in typical contexts and with macroscopic models, which show mean scores in the range of 50%–60%. These questions can often be solved using memorization-based strategies. However,

TABLE III. Pretest data of the intervention and control classes.

Question set	Group	Mean	SE	t	p
Total	Control	40.47	1.63	1.61	0.112
	Intervention	43.65	1.12		
Single link	Control	55.60	2.33	1.98	0.051
	Intervention	61.90	2.17		
Multilink	Control	39.32	2.40	0.33	0.741
	Intervention	38.31	1.87		
Integrated link	Control	21.22	1.97	1.83	0.071
	Intervention	25.89	1.62		
Typical	Control	52.56	2.16	1.30	0.197
	Intervention	56.35	1.94		
Atypical	Control	28.37	1.90	1.12	0.266
	Intervention	30.95	1.30		
Macroscopic	Control	48.98	2.12	1.54	0.127
	Intervention	53.42	1.94		
Microscopic	Control	30.73	2.08	0.68	0.497
	Intervention	32.48	1.50		

students had very low scores (20%–30%) on integrated link questions in atypical contexts and with the microscopic model, which require an understanding of the central idea of electric current. The results suggest that most students lacked the understanding of the central idea (i.e., the microscopic model of electric current) and were at a low level of knowledge integration before high school instruction. Students relied heavily on memorization-based strategies in problem solving and were unable to solve problems in unfamiliar contexts such as the atypical questions.

B. The impact of conceptual-framework-based instruction mode on students' conceptual learning

The assessment outcomes of the pretest, post-test, and delayed post-test for the control and intervention groups are plotted in Fig. 2 and are analyzed using t tests and Cohen's d effect sizes for statistical significance and impact (see Table III). The results suggest that the conceptual-framework-based instruction can promote knowledge integration in learning, which is discussed in detail next.

Comparing the total scores of the control and intervention groups on the three tests, it is obvious that both groups had improved performance on post-test scores over their pretests, with the intervention group achieving nearly twice as much score gains ($p < 0.001$, $d = 1.181$ vs $p = 0.050$, $d = 0.454$). The results suggest that the modified instruction had a better overall effect on improving students' conceptual understanding than the traditional instruction. When comparing the results of the delayed post-test, the effects are more dramatic. Although both groups had negative changes in their post-test to delayed post-test scores, the decay for the intervention group was minimal and insignificant ($p = 0.518$, $d = 01.65$), while the change for the control was nearly 6 times larger than that of the intervention group ($p = 0.002$, $d = 0.82$). The results indicate that the modified instruction was able to help students achieve much better retention of the correct understanding than the traditional instruction. These outcomes were consistent with our expectation and hypothesis that the modified instruction can promote the development of a more integrated knowledge structure, with which students can engage in meaningful reasoning to solve physics problems. This type of deeper and well-connected understanding is more resilient to forgetting, which leads to

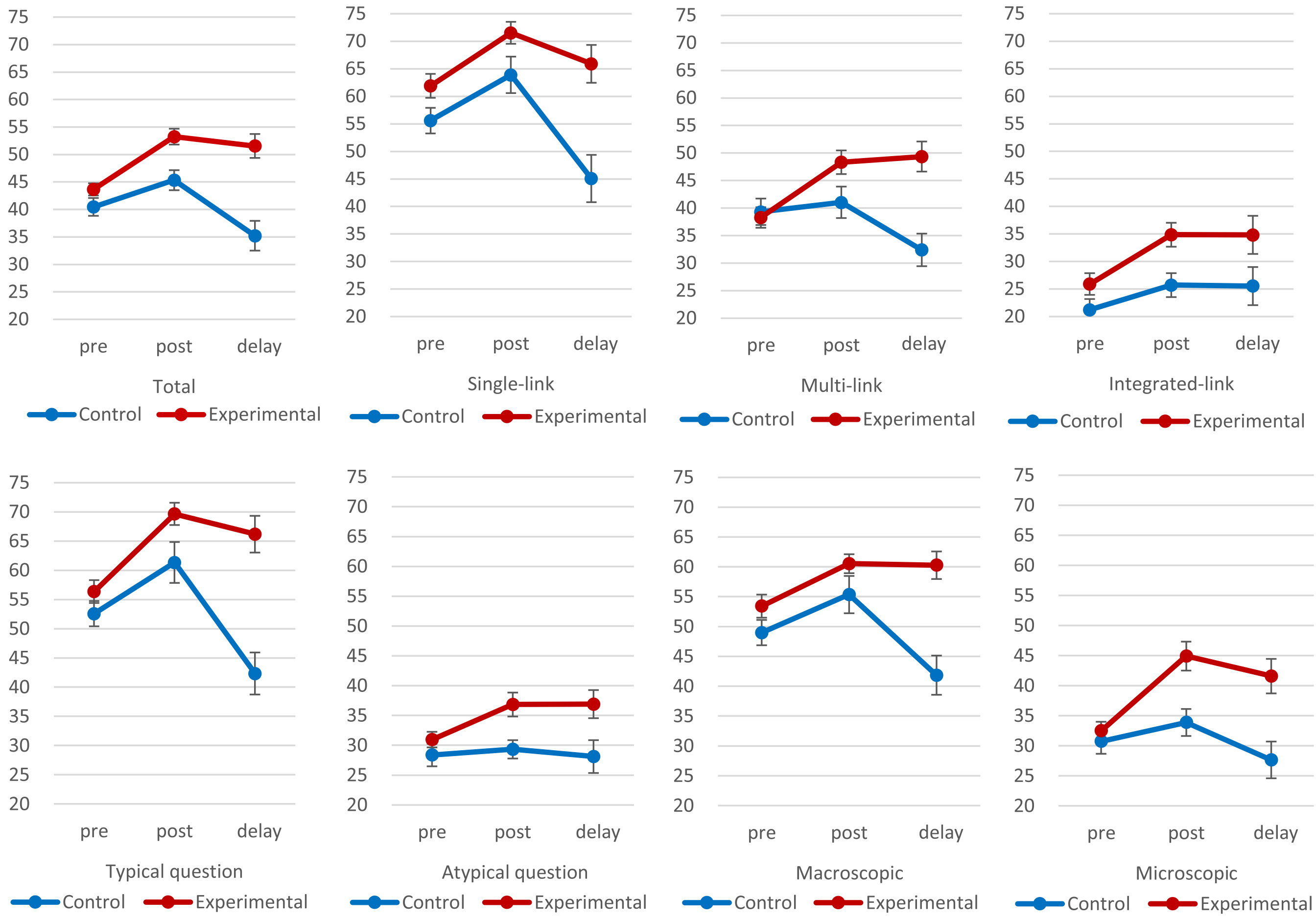

FIG. 2. The total scores and scores of different question types on the pretest, post-test, and delayed post-test for the control and intervention classes. The error bars represent the standard errors of the means.

better retention of the learning outcomes. In contrast, traditional instruction often promotes rote-based learning, and the memorized fragments are not meaningfully connected, making them highly susceptible to forgetting.

Looking into the score patterns of different question sets, the effects of the instruction can be more clearly demonstrated. For the questions designed with single-link, typical context, and macroscopic models, similar pre-post score gains were observed in both the intervention and the control groups (the two pre-post lines are nearly parallel). The results suggest that on these simpler questions that do not need to engage the central idea, traditional instruction is effective in helping students converge on the correct answers; however, such learning is largely rote based, which is evidently shown by the dramatic decays in scores on the delayed post-test. In contrast, the intervention group's scores on the delayed post-test are somewhat lower than the post-test scores, but the differences are not statistically significant (see Table II). The results further demonstrate that the modified instruction can help students gain a deeper conceptual understanding even with the simple questions that usually do not require the use of the central idea.

For questions designed with integrated links, atypical context, and microscopic models, students are expected to use the central idea in reasoning and solving these questions. Consequently, it is expected that the modified instruction would have better effectiveness on learning, which is evident from the larger pre-post score gains achieved by the intervention group when compared to the control group with which the gains are statistically insignificant (see Table IV). What is most interesting is that the score decays on the post-test were insignificant for both groups on all question sets. This is a very important outcome, revealing that when students learn to understand and apply the central idea through any type of instruction, their knowledge is resistant to forgetting. That is students in all instruction conditions will have the opportunity (with different probabilities) to learn and understand the central idea, and once learned, this knowledge will be retained and applied in meaningful reasoning for solving problems, which makes it fundamentally different from rote-based

TABLE IV. Statistical analysis of test outcomes.

Question set	Group	Test	Score changes	*t*	*p*	Cohen's *d*
Total	Intervention	Post-pre	9.595	5.302	<0.001	1.181
		Delayed-post	−1.698	0.651	0.518	0.165
	Control	Post-pre	4.868	1.995	0.050	0.454
		Delay-post	−10.116	3.230	0.002	0.850
Single link	Intervention	Post-pre	9.626	3.234	0.002	0.726
		Delayed-post	−5.622	1.417	0.163	0.363
	Control	Post-pre	8.294	2.105	0.039	0.473
		Delayed-post	−18.837	3.516	<0.001	0.938
Multilink	Intervention	Post-pre	10.014	3.510	<0.001	0.784
		Delayed-post	1.025	0.297	0.768	0.073
	Control	Post-pre	1.715	0.464	0.644	0.105
		Delayed-post	−8.628	2.030	0.047	0.554
Integrated link	Intervention	Post-pre	8.976	2.780	0.007	0.629
		Delayed-post	−0.047	0.012	0.991	0.003
	Control	Post-pre	4.493	1.530	0.130	0.348
		Delayed-post	−0.171	0.044	0.965	0.011
Typical	Intervention	Post-pre	13.300	4.845	<0.001	1.086
		Delayed-post	−3.459	0.987	0.328	0.239
	Control	Post-pre	8.775	2.133	0.037	0.495
		Delayed-post	−19.014	3.649	<0.001	0.998
Atypical	Intervention	Post-pre	5.890	2.462	0.017	0.556
		Delayed-post	0.063	0.020	0.984	0.005
	Control	Post-pre	0.961	0.380	0.705	0.088
		Delayed-post	−1.217	0.415	0.680	0.107
Macro	Intervention	Post-pre	7.104	2.788	0.007	0.628
		Delayed-post	−0.258	0.095	0.924	0.023
	Control	Post-pre	6.375	1.690	0.096	0.458
		Delayed-post	−13.509	2.882	0.006	0.786
Micro	Intervention	Post-pre	12.442	4.382	<0.001	0.991
		Delayed-post	−3.343	0.895	0.374	0.223
	Control	Post-pre	3.147	1.023	0.309	0.233
		Delayed-post	−6.238	1.675	0.100	0.445

memorization. Therefore, knowledge learned in this way will be part of an integrated knowledge system and cannot be easily forgotten. This feature of knowledge development demonstrates that learning the central idea defined in the conceptual framework is an evident indicator of the broadly defined learning outcome for achieving knowledge integration and deep understanding.

Synthesizing the results, an encouraging outcome is observed in this study, suggesting that the conceptual-framework-based instruction can promote expertlike deep thinking in different contexts and complexity. The results from the complex questions with atypical contexts further demonstrate that this expertlike thinking is equivalent to achieving a good understanding of the central idea defined in the conceptual framework model.

IV. CONCLUSIONS

In our previous study, a conceptual framework model of simple electric circuits was established and applied to develop an assessment tool for probing knowledge integration in student learning of simple electric circuits [36]. The assessment results revealed that many students failed to effectively understand the micromodel, and very few students were able to comprehend the central idea. To address this problem, this study conducts a follow-up investigation that applies the conceptual framework to develop an instructional intervention that aims to promote knowledge integration in students' learning of simple electric circuits. Guided by the conceptual framework model of simple electric circuits, the modified instruction placed an explicit emphasis on helping students develop a thorough understanding of the central idea and establish connections between the central idea and other knowledge components. This approach was expected to enhance students' knowledge integration in learning.

The instructional intervention was implemented in an intervention group, which was compared with a control group that used the existing instruction. Data were collected from both groups through multiple common assessments including a pretest, a post-test, and a delayed post-test using the instrument developed in our previous study [36]. The results show that the intervention group achieved significantly larger pre-post score gains than the control group both in the overall performance and in all question sets targeting different contexts, complexity, and conceptual models. In addition, students in the intervention group also had much better retention of their learning outcomes on the delayed post-test than the control group. The results demonstrate that the intervention is effective in transforming students' learning from rote-based memorization to deeper conceptual understanding. In particular, the different patterns of score decays across easy and hard questions on the delayed post-test between the intervention and control groups revealed that the intervention was successful in helping students learn the central idea and apply it proficiently in solving problems with wide variability in contexts, complexity, and conceptual models. The results further suggest that understanding the central idea is a critical indicator of achieving knowledge integration.

Regarding the assessment methodology, the delayed post-test proved highly effective in capturing distinctive student learning behaviors, allowing for clearer differentiation between memorization and deep understanding. This approach provided a means to probe the type of learning that occurred during instruction and the level of knowledge integration achieved by students. The inclusion of the delayed post-test strengthens the impact of the experiment. Demonstrating differences in score decay across different problem types, not only confirms that this instructional approach can facilitate knowledge integration but also supports the validity of this assessment model from the perspective of cognitive information processing theory [51–53]. This type of assessment method can provide effective utility in future studies on knowledge integration.

Although encouraging outcomes have been observed, there are limitations to this research, which should be further examined in future studies. In this investigation, the sample size was small and limited to the specific education setting. Therefore, the results of this study should be carefully interpreted when extending to other populations and education contexts. Research with a larger number of students in different education settings would be beneficial to further validate the conclusions and to explore possible variations in the learning characteristics of different student groups. Furthermore, the delayed post-test was administered 2 weeks after the post-test, which showed clear distinctive comparisons between the different groups and question sets. It would be interesting to explore how students' performance may differ with different delay periods, with which an optimal delay time may be obtained.

In summary, the results of this study show that the conceptual-framework-based instruction is effective in promoting knowledge integration and deep learning, which is consistent with a number of existing studies on other content topics [16,17,32]. The results also show that the delayed post-tests can be an effective method to assess the level of student's conceptual understanding and provide quantitative evidence for exploring whether students are using memorization or deep learning in problem solving.

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APPENDIX

This is an example question the Test of Knowledge Integration in Electric Circuits (TKIEC) selected to demonstrate how understanding the central idea and the microscopic model of current is essential for solving the problem correctly. For this example, students must reason between macroscopic and microscopic models under the guidance of the central idea. They need to comprehend the microscopic nature of resistance, current, and voltage, and the relationships between them to solve the problem. Students who merely memorize the equation $V = IR$ will not be able to solve this problem correctly. Therefore, being able to solve such problems indicates achieving a deep understanding of the central idea.

30. Two cylindrical rods with the same length and cross-sectional area made of different metal conductors are connected in series and then connected to both ends of a dc power supply, as shown in Fig. 3. $R_a > R_b$. When the current reaches a constant level, if there is an electric field in a and b, the electric field can be regarded as a uniform electric field. The correct conclusion below is

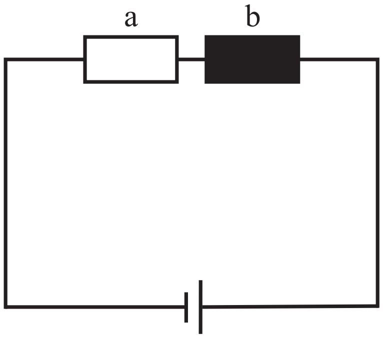

FIG. 3. Circuit diagram for question 30.

A. The electric field in the two rods is not equal to zero, and the electric field in a is greater than that in b.
B. The electric field in the two rods is equal to zero.
C. The speed of free electrons' directional movement in the two rods must be equal.
D. The speed of free electrons' directional movement in a must be greater than that in b.
E. Because $R_a$is greater than R_b, the current $I_a$is smaller than I_b.

Explanations to answer choices:

A. This is the correct answer. In a series circuit, the potential difference across resistor A is larger than that across resistor B. Since the lengths of the two resistors are identical, the electric field in resistor A must be larger than that in resistor B. This is because the electric field multiplied by the length gives the potential difference.
B. Because the directed movement of charge is driven by an electric field, and there is an electric current in both rods, the electric field within each rod is not zero.
C. Although the two rods are connected in series and the magnitude of the current passing through them is equal, the microscopic expression for current ($I = qnvS$) indicates that the current depends on multiple variables, including electron density. Since the materials of the two rods are different, the electron densities can vary. Consequently, the velocity of the directed movement of free electrons may not be the same in each rod.
D. As explained in C, there are multiple uncontrolled variables and the conclusion in D cannot be warranted.
E. In a series circuit, the current is the same everywhere.

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