Assessment of knowledge integration in student learning of simple electric circuits

Zengze Liu,[1,2] Sudong Pan,[1,†] Xiangqun Zhang,[2,3] and Lei Bao[2,*]

[1]*East China Normal University, Faculty of Education, Shanghai 200062, China*
[2]*The Ohio State University, Department of Physics, Columbus, Ohio 43210, USA*
[3]*Zhenjiang Experimental School, Zhenjiang, Jiangsu 212034, China*

(Received 15 November 2021; accepted 10 June 2022; published 11 July 2022)

Student learning in simple electric circuits has been extensively studied, which has revealed a large number of persistent misunderstandings. This study applies the conceptual framework model to investigate student difficulties in the knowledge integration perspective. The results are used to guide the design of a concept test that targets the different stages of knowledge integration in student learning of electric circuits. Specifically, two areas of research have been conducted. First, based on content analysis by experts and a review of the literature on students' conceptual understandings, a conceptual framework for electric circuits is developed. The conceptual framework model is then applied to guide the development of a multiple-choice concept test for assessment of knowledge integration in learning electric circuits. Both qualitative and quantitative data were collected from high school students who had completed the learning of electric circuits. The results confirmed that the conceptual framework model can effectively represent the knowledge structures of students at different levels of knowledge integration. In addition, the assessment outcomes also reveal that the concept test is effective in identifying unique features of knowledge integration, including context dependence and fragmentation of knowledge components, memorization-based problem solving, difficulty in transfer to novel contexts, and lack of meaningful connections between microscopic and macroscopic models of electric current. The assessment outcomes can also provide practical information for instruction to promote knowledge integration in learning electric circuits.

DOI: 10.1103/PhysRevPhysEducRes.18.020102

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]. Although these students are often able to solve problems with familiar designs and contexts, they are likely to fail on problems using novel contexts or requiring deeper conceptual understanding. Existing studies have demonstrated fundamental differences between experts and novices in their knowledge structures [10–15]. Experts usually are able to develop an integrated knowledge structure, where different components and connections of knowledge are integrated around the central idea of a concept. In contrast, the knowledge structures of novice students are often fragmented with local connections between features of contexts and memorized problem-solving procedures and outcomes [10–15].

To promote knowledge integration and deep understanding in teaching and learning, it is beneficial to model students' conceptual understandings through the knowledge integration perspective [16]. In recent studies, a conceptual framework model has been developed to specifically target aspects of knowledge integration in learning physics [17–20]. The conceptual framework model is a concrete instantiation of the generally defined knowledge integration perspective. It provides an operational 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 modeling the features of students' knowledge integration, the conceptual framework model distinguishes students into several developmental levels such as novice, intermediate, and expert [17–21]. Novice students often develop fragmented knowledge structures with locally linked knowledge pieces that are tied to specific contexts and have limited ability to transfer and apply their understanding in novel contexts. When solving problems, these students often focus on the surface features of the problems, and directly match these contextual features with memorized algorithms, equations, and examples [14,22–24].

[*]Corresponding author.
bao.15@osu.edu
[†]Corresponding author.
sdpan@phy.ecnu.edu.cn

For intermediate students, many have developed more extended connections in their knowledge structures, but they still have limited understanding of the central idea and its connections to contextual features and operational rules. In problem solving, these students can demonstrate improved understanding compared to the novices; however, they often fail to solve problems with unfamiliar settings, which limits their capability of transferring their understandings to new contexts [15,25,26]. Students at this level still have a tendency to rely on memorized equations and procedures. Expert-level students are able to construct an integrated knowledge structure that is well organized around the central idea, which demonstrates achieving a deep understanding of the concept and enables the students to apply their understandings across various contexts to solve problems in a wide range of settings.

The conceptual framework model of student learning is content specific, and a unique framework needs to be developed for each specific concept topic. The development of a conceptual framework for a particular concept starts with identifying the central idea of that concept, along with contextual variables and relations relevant to the concept. Subsequently, the conceptual pathways can be built among the central idea and other elements related to the concept [17–20]. Once a conceptual framework on a specific topic is established, it can be employed to develop assessment instruments that target students' knowledge structures with a focus on aspects of knowledge integration in students' conceptual understanding. In a number of recent studies, the conceptual framework model has been applied to several topics in physics, including light interference [17], force and motion [21], momentum [18], wave propagation [20], and Newton's third law [19]. The results have demonstrated the utility of the conceptual framework model in guiding assessment and instruction to promote knowledge integration in student learning.

Student learning of simple electric circuits has been extensively researched, which has revealed significant learning difficulties and persistent misunderstandings [3,27–30]. These misunderstandings are widely distributed in concepts such as voltage, current, and resistance [31–37], and are persistent among populations at all developmental stages [27,38,39]. There are many factors that may contribute to students' developing misunderstandings, including personal experience, aspects of instruction, and presentations in the textbooks [40]. In addition, the content itself is quite challenging for students at all ages. The topic of electric circuit is a complex system of entangled concepts, involving both macroscopic phenomena and microscopic models. For example, the concept of resistance is macroscopically described as impedance to the flow of electric current, which is mechanistically explained with a microscopic model of collisions between electrons and atoms in the conductor. Therefore, achieving a good understanding of electric circuits requires students developing an integrated knowledge structure connecting both macroscopic phenomena and operations with microscopic mechanisms in a coherent system.

In this research, a conceptual framework model of simple electric circuits is developed and applied to guide the assessment on students' levels of knowledge integration in learning electric circuits. Specifically, two areas of research are conducted:

Part 1: A conceptual framework model of electric circuit is developed and applied to analyze the existing work on students' conceptual understanding of electric circuits from the knowledge integration perspective.

Part 2: The conceptual framework model developed in Part 1 is used to guide the development of a multiple-choice test to measure students' levels of knowledge integration in learning electric circuits. Interviews and quantitative analysis are conducted to further validate the conceptual framework and the assessment design.

II. PART 1: DEVELOPMENT OF A CONCEPTUAL FRAMEWORK MODEL OF SIMPLE ELECTRIC CIRCUITS

A. Expert views and student understandings of simple electric circuits

The domain knowledge of electric circuits involves several main conceptual ideas including macroscopic concepts on voltage, current, resistance, Ohm's law, electromotive force, series and parallel circuits, as well as the microscopic models based on the concepts of point charge, electric field, electric potential, force and motion of charge, and conservation of charge [36,41,42]. Here, the macroscopic concepts describe the observed features and relations of the descriptive variables of a circuit, while the microscopic models provide mechanistic explanations on how the observed phenomena can happen, leading to a deeper understanding of electric circuits. At the introductory level of physics, the operation of a circuit can be fundamentally explained with the understanding that a charge in an electric field is subjected to an electric force due to the field, which can lead to acceleration and motion of the charge. In the situation of a conductor, motions of electric charges (typically electrons) can be impeded by collisions with microscopic particles that constitute the conductor. This mechanistic understanding, which is defined as the central idea of electric circuits, can then integrate the related concepts into a coherent understanding that mechanistically explains the macroscopically observed relations among current, voltage, and resistance, which further contributes to developing a deep understanding of how an electric circuit works.

In the context of simple electric circuits, applying the central idea can develop several key understandings including the microscopic current model $I = q/\Delta t = neSv$, which connects current with the motion of charges (such as its density and velocity), and the voltage (aka potential difference) between two nodes, $V_{AB} = W_{AB}/q = Ed = \phi_A - \phi_B$, which connects voltage with electric field, electric potential, charge, and energy [41–45]. In particular, the understanding of microscopic mechanisms of electric current has also been previously documented as an essential element in distinguishing expert and novice learners [46]. Following the conceptual framework model, the expert level of understanding is operationally defined based on whether students have developed a good understanding of the central idea and can apply it to connect all the related microscopic and macroscopic concepts into a coherently integrated knowledge structure.

On the other hand, as well documented in the literature, novice leaners often have widespread difficulties in understanding the concepts in electric circuits [27,31–34,38,39]. Some of the common student misunderstandings are summarized below:

1. Common misunderstandings of current

Students often have difficulties in understanding the nature of electric current being a flow of electric charges, which requires a closed circuit and is continuous throughout the closed circuit. Novice students often fail to recognize the need for a closed circuit, and therefore treat electric components as "electric sinks" that transform the current sent by a battery into other forms of energy such as light and/or heat [31,40]. Similarly, a current can be considered to attenuate in a circuit, whereby the current leaving a battery from one end is used up by the components in the circuit, and the unused portion returns back to the other terminal of the battery [31,33,34,40]. In addition, when analyzing circuit networks such as a parallel or series circuit, the current in the circuit can be considered by students as a sharable entity; i.e., the current going out of a battery is shared and used up in the different components in the circuit [31,33,34,40]. These naïve views demonstrate the deficit in understanding the microscopic mechanism of electric current.

2. Common misunderstandings of voltage

For voltage related concepts, students often have difficulties to distinguish among electromotive force, voltage, and electric potential difference [37,47]. Some students think that voltage is the product of current, which cannot exist without current. This indicates a direct readout of the equation $V_{AB} = IR$, where voltage is conceived as a mere outcome of a mathematical relation, an attribute or a property of current rather than its cause [31,33]. In situations involving batteries or power supplies, students tend to think of a power supply as a constant current source that provides a constant current to a circuit [31–34]. Students may also think of voltage as an absolute measure defined at a point, rather than the potential difference between two points [31–34,46]. In addition, students may believe that voltage only exists in a closed circuit [32]. These difficulties indicate that many students fail to develop an understanding of the microscopic model of current. Without this understanding, the relations among voltage, current, and other related concepts become contextualized language puzzles, which can only be memorized as mathematical equations.

3. Common misunderstandings of resistance

Research has also revealed that students often fail to develop a conceptual understanding about resistance and its role in a circuit [27]. Novice students often interpret resistance with the equation $R = V_{AB}/I$, as a mere mathematical link between voltage and current. Students also develop naïve conceptions thinking that resistance "consumes" electric charges while acting as the locus of current dissipation in the form of heat or light [31,33]. In circuit analysis, students often have difficulties in distinguishing between equivalent resistance of a network and resistance of an individual element, especially when accounting for a dynamic change [31,38]. Many students tend to focus on surface features such as the number of elements or the number of branches rather than on the configuration structure of a circuit, and thus have problems in accepting that the equivalent resistance of a parallel network decreases when the number of components increases [31,38]. Regarding the relation between resistance and current, some students may view resistance as being caused by the current, thinking that a resistor resists the current, so a current must flow in order to have any resistance [3]. Holding such views, many students often have difficulties in understanding the mechanism of the relation between voltage across a resistor and the current going through the resistor [31,38,48]. These student difficulties again indicate the lack of understanding of the microscopic model of current as charge flow in an electric field within a circuit, which explains the resistance as an observed macroscopic measure of the impedance to the motion of electric charges due to microscopic properties and structures of the material.

4. Common misunderstandings of circuit networks

At the introductory physics level, analysis of circuit networks mostly focuses on the series and parallel connections. Existing studies have documented a wide range of student difficulties in understanding and analyzing circuit diagrams. For example, in analyzing multicomponent circuits, students often lack a global view of a circuit and tend to focus their attention on one part of the circuit, ignoring what is happening elsewhere [34,35,49]. In analyzing circuits in realistic or complex settings, students often exhibit difficulties in translating realistic circuits into schematic diagrams or vice versa. Identifying series and parallel networks from nonstandard circuit diagrams is also very challenging for students. They often fail to realize that a circuit diagram represents electric connections not the actual physical layout [31]. Students may also have difficulties in understanding and identifying short and open circuits [49].

Although on the surface, the students' difficulties in analyzing circuit networks may not appear to be directly related to the central idea; however, it can be argued that without a deep understanding of the relations between voltage, current, and resistance, analysis of circuit networks can be mostly a topological game relying on memorized procedures and rules. During learning, different aspects of students' conceptual understandings of current and voltage are likely to influence their reasoning in circuit analysis. For example, students often think that the bulbs that are further away from the power supply are dimmer than the closer bulbs, where the distance from the power supply is considered more important than how the bulbs are arranged in a circuit [33,34]. This indicates that students may hold the naïve view of current being used up in a circuit and apply this idea in analyzing circuits.

Synthesizing the literature on student difficulties in learning electric circuits, it is evident that many students fail to develop an integrated understanding that coherently explains and connects the related concepts. These students often develop fragmented knowledge structures and rely on memorized procedures and equations in problem solving. Although these students may be successful in solving standard problems with familiar contexts, they often fail to meaningfully interpret their calculations to predict or justify the behaviors of real electric circuits. This indicates that students' knowledge is mostly procedural and lacks a deep conceptual understanding [31–33]. In addition, students often have difficulties in understanding the microscopic models of electric current, potential, and resistance, which are crucial for developing an integrated knowledge structure of electric circuits.

The review of literature discussed here can provide useful resources for modeling student learning from the knowledge integration perspective. In the next section, a conceptual framework is developed and applied to model and measure the different aspects of knowledge integration in student learning of electric circuits.

B. Developing a conceptual framework model of electric circuits

The components and structures of a conceptual framework model are identified or developed based on experts' analysis of the physics content and students' learning behaviors documented in the literature. The developed conceptual framework represents a hypothetical model for representing students' knowledge structures. The validity of the model is evaluated in two sets of analysis including Sec. II C, which compares the model with existing literature to provide arguments for the relevance of the conceptual framework in modeling students' learning behaviors, and the analysis of quantitative assessment and interviews in the later part of the paper, which examines the consistency between the model and empirical measurements.

The first step to develop the conceptual framework model is to identify the central idea of the related concepts on electric circuits, which was conducted by a team of experts including two faculty and two graduate students in physics. The team reviewed the related textbooks and research articles on student difficulties, which are used as the basis to identify the central idea. After extensive discussions among members of the expert team, the central idea of electric circuits is identified to be the microscopic model that mechanistically explains how an electric circuit works: "*The charges in a conductor are conserved and have random motion. When forces are applied to the charges due to an electric field (E-field), the charges 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.*" Building off the central idea to include different operational rules and reasoning processes from experts and students, the conceptual framework of electric circuits is developed and shown in Fig. 1.

The conceptual framework is structured in a hierarchy of four layers of constructs with the central idea at the top, representing the most fundamental core understanding underlying the complete knowledge structure. The bottom layer contains contextual features and variables, which are the most concrete aspects of physical scenarios commonly used as components of the problems on electric circuits. These include different conditions and measures of voltage, current, and resistor, as well as different networks and forms of circuit diagrams.

The two middle layers, which are numbered second and third counting from the top, contain intermediate reasoning processes and operational rules and procedures. The second layer includes the microscopic models and operations, which directly connect to the central idea in experts' knowledge structures. Links to these models are rarely developed among novice students. The third layer includes macroscopic models and operations. In an expert's knowledge structure, the third layer macroscopic models are well connected to and explained by the second layer microscopic models and the top layer central idea, which are operationally applied to manipulate the fourth layer contexts and variables to solve problems with a meaningful conceptual understanding. For novices, these macroscopic models and operations are often in the forms of memorized terms, equations, and procedures with little deeper conceptual understanding. These students also tend to develop local links through incorrect or partially correct reasoning with memorized equations between the third layer models and the fourth layer contexts and variables. These local links form the memorized connections that match between contexts and results or problem-solving procedures.

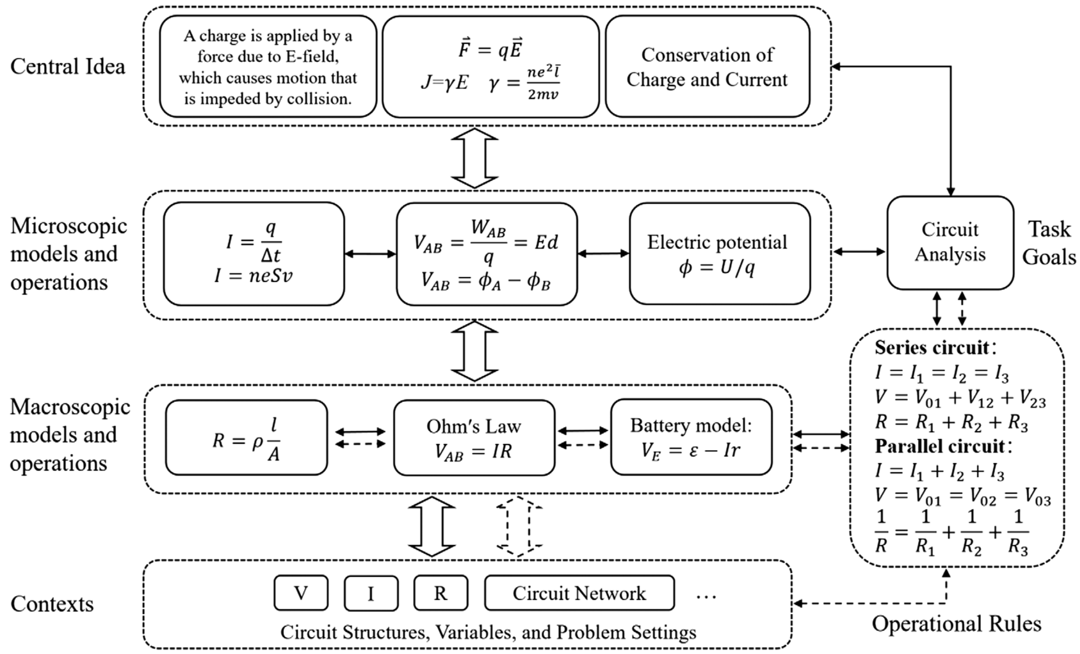

FIG. 1. The conceptual framework model of electric circuits. The solid arrows represent the conceptual pathways of experts, and the dashed arrows represent the conceptual pathways of novice students. Intermediate level students often have mixed use of expert and novice pathways.

The conceptual framework forms the backbone for analyzing how learners reason in problem solving by combining these layers and the task goals, with arrows connecting different contextual, conceptual, and operational components to represent the possible reasoning pathways of learners. Solid arrows represent experts' conceptual pathways, while the dashed arrows represent pathways of novices. As discussed earlier, these pathways and the conceptual framework itself are constructed based on experts' analysis of the physics content and literature on student difficulties through the knowledge integration lenses, which will be further evaluated through quantitative assessment and interviews in later part of the paper.

C. Modeling student understanding using the conceptual framework

Using the conceptual framework, student misunderstandings and difficulties documented in the literature can be represented with thinking pathways, which can be further analyzed to identify students' levels of knowledge integration. In previous research, a number of developmental levels were identified through large scale testing and interview studies [18–21]. Differences between the levels were found to be directly related to performance and reasoning on assessment questions addressing different thinking pathways in student knowledge structures. In this study, the conceptual framework model is applied to analyze the student difficulties documented in the literature, which reveal three levels of conceptual development discussed below:

1. Novice level

The knowledge structures of novice students are typically fragmented with only local connections linking contextual features to operations and questions in the macroscopic models. These novice thinking pathways are shown with the dashed arrows in Fig. 1. For these students, understandings of the microscopic models and the central idea have not yet been established, and they mainly rely on matching problem contexts with memorized equations to solve problems, which can be shown as a thinking pathway of "problem context → macro model or operational rules (equations) → solutions" in Fig. 1.

For example, in solving a circuit problem, novice students often focus on variables such as current, voltage, and resistance from the problem context and plug these into the Ohm's law equation $V_{AB} = IR$ to find answers for current and voltage [31,33,34,40]. However, although these students may successfully apply the equations to calculate voltage, current, and resistance in limited situations, most of them lack the conceptual understanding of how a circuit works and cannot predict or explain the behavior of a simple real circuit. When analyzing circuit networks, novice students tend to focus on the number of components and branches rather than on the configuration [27,38]. The results suggest that novice level students can only memorize and operationally apply the equations and procedures in the macroscopic models to solve problems, without developing an understanding of the underlying microscopic principles and the central idea.

2. Intermediate level

Students at this level can engage in a deeper level of reasoning to develop more connected understanding with the contextual variables than the novice students; however, these students still tend to rely on memorized examples and procedures to aid their problem solving but to a lesser extent than the novice students. The increased integration within their knowledge structures include some understandings of the microscopic models, which allow students to think about a few isolated parts of the microscopic models in limited familiar problems. However, these students' understandings of the microscopic models mainly consist of memorized effects and terms in limited contexts. Understandings of the mechanistic relations among microscopic variables and their connections to the central idea are often lacking. As a result, most students at this level are not capable of applying the microscopic models to explain the related macroscopic phenomenon and rules. With only weak understanding of the microscopic models and central idea, students at this level often fail on questions with unfamiliar novel contexts [19]. They usually exhibit diverse, rich behaviors with mixed understandings on conceptual aspects [25], where a typical thinking pathway often vacillates between microscopic and macroscopic reasoning such as going through "problem context → macro − model → micro model → macro model → operation rules → result."

For example, students at this level often can realize that the magnitude of the current is related to the density of free charges and the average group speed of charges. They can also identify the related macroscopic variables to calculate the current density using the equation $j = \rho v$. However, many of them have not established the correct understanding of the relations between the motion of charges and the electric field in a circuit. These students only have the memorized description that a current is a charge flow in a closed circuit, but they lack the mechanistic understanding of how electric field is created by a potential difference in a circuit and how it drives the charge flow [27,35,36,49]. In addition, most students at this level also lack the conceptual understanding of the microscopic model of resistance and its connections to circuit behaviors [27,35,36]. They can work with the macroscopic equation $R = \rho l/A$ involving factors such as the material, length, and cross-sectional area of a resistor to determine the resistance but do not understand the microscopic mechanism underlying the macroscopic behaviors. These students often fail on questions asking about the influence on resistance from temperature, which needs to be explained from the motion and collision of the microscopic particles, a concept that is often not established among intermediate-level students [46,50].

3. Expert level

Students at this level have developed a good understanding of the central idea and the microscopic models with a well-integrated knowledge structure. This allows them to relate contextual variables to the central idea, along with the microscopic and macroscopic operations and procedures, to form a comprehensive web of connections that can address a wide range of problems with familiar and novel contexts. For example, these students recognize that the electric field provides the driving force for free charges to move in an electric circuit and can relate electric field to the potential difference in a circuit. They also understand the related microscopic models such as the resistance model that the motions of charges are impeded by collisions as well as the conductor model that the total charges are neutral with abundant free-to-move electrons. The proper understandings of the central idea and the microscopic models help students to mechanistically explain macroscopic phenomena such as the conservation of charges and total current being conserved in a circuit. These understandings also allow students to correctly explain and solve more conceptually challenging questions such as why the current is nearly instantaneously observed after the circuit is turned on [26,42,48].

Using the conceptual framework, the reasoning pathways of students at different developmental levels can be clearly analyzed from the knowledge integration perspective. The expert-level students have developed a fully connected knowledge structure allowing them to reason from any given point of context or conceptual component to reach the central idea, which can further activates the entire knowledge hierarchy to analyze different problem scenarios and transfer from familiar contexts to novel situations. In contrast, novice students often focus on the surface features of contexts and specific variables, which are mapped directly to memorized equations for solving problems. The knowledge structures of the novice students are largely fragmented with local links connecting specific contexts and memorized macroscopic rules, which result in significant context dependence and poor transferability of their knowledge. As indicated from the analysis, the understanding of the central idea and the connections between macroscopic and microscopic models appear to be the most essential cornerstone that students need to develop in order to achieve the expert-level understanding.

To summarize, in this part of the research, a conceptual framework of an electric circuit has been developed based on the experts' analysis of the key concepts and a review of literature on student learning difficulties. Using the conceptual framework, student learning can be modeled in terms of three levels of knowledge integration based on the difference in the conceptual connections that students demonstrate in solving problems of different complexity and contextual settings. Utilizing these modeling features, assessment on student knowledge integration is developed and discussed next.

III. PART 2: ASSESSMENT OF KNOWLEDGE INTEGRATION IN STUDENT LEARNING OF ELECTRIC CIRCUITS

A. Assessment design

In the literature, many studies have been conducted to identify and assess student conceptual understandings of electric circuits [3,31–34,38,40]. However, the related assessments were not designed to evaluate the levels of students' knowledge integration. Hence, this research will extend the current assessments to target students' knowledge integration in learning electric circuits. Several recent studies have demonstrated the effectiveness of conceptual-framework-based assessments on measuring knowledge integration and deep understanding [17–21]. These assessments take advantage of question design features including knowledge connectedness and contextual saliency, which can be directly linked to levels of knowledge integration [19,20].

The contextual saliency of assessment questions is manipulated with a mixture of typical and atypical questions, which is a strategy shown effective in designing conceptual-framework-based assessment [19,20]. Typical questions contain contextual settings that the students often encounter in lectures, textbooks, and homework, which can be solved with memorized equations and problem-solving procedures. On the other hand, atypical questions are designed with unfamiliar contexts that require the use of the central idea to solve correctly.

The design of knowledge connectedness follows the knowledge integration rubric developed by Linn *et al.* [16,51,52], which is also similar to the link types defined in the taxonomy of structure of the observed learning outcomes (SOLO) [53]. The original link types have been simplified into three levels including single link, multilink, and integrated link [20]. The single-link problems only require students to establish a single connection between certain contextual features and operational rules, which can often be solved correctly by memorizing the related procedures and operations. The multilink problems require students to establish connections between contextual features and multiple conceptual components and operations; however, these connections are often locally linked without extended pathways to engage the central idea. On the other hand, to solve the integrated-link problems, students need to understand the central idea and develop an integrated knowledge structure centered around the central idea.

In addition, as shown in Fig. 1, the conceptual framework of electric circuits has a unique distinction between types of conceptual understandings in terms of microscopic and macroscopic models, which provides an additional question design feature that can be used in assessing knowledge integration. The microscopic models are the instantiations of the central idea for explaining the mechanisms of the circuit operations at the microscopic level, which include models of conductor, resistance, current, electric field, and electric potential. Therefore, assessment of students' knowledge of microscopic models can be directly used to evaluate their understandings of the central idea. On the other hand, the macroscopic models provide operational rules and equations that can be directly used to solve problems on circuit analysis.

In this study, the assessment design for measuring student knowledge integration will utilize all three features discussed above, including contextual saliency with typical and atypical contexts, knowledge connectedness with three link types, and deep conceptual understanding with microscopic and macroscopic models. Based on the student behaviors discussed earlier and demonstrated in the existing studies [17–21], it is expected that the three main features of question design should produce measurement outcomes for distinguishing and categorizing students at different knowledge integration levels.

For example, on the design feature of typical and atypical questions demonstrated from previous studies [17–21], novice students can be moderately successful in solving the typical questions but will fail on most atypical questions. Meanwhile, intermediate level students are often able to solve most typical questions but have weaker and inconsistent performances on atypical questions. When students achieve the expert level, they are able to solve both types of questions consistently.

In solving questions with different link types [20], novice students are often moderately successful on single-link questions but will fail on multilink and integrated-link questions. Intermediate students are usually successful on most single-link and many multilink questions but with only occasional success in solving integrated-link problems. For expert-level students, they are able to solve problems designed with all three link types, especially the integrated-link problems, which is a criteria demonstrating an integrated knowledge structure [12].

On questions contrasting microscopic and macroscopic models of electric circuits, novice students can be successful on limited typical questions involving the macroscopic models. These students will usually fail on any type of questions requiring some understanding of microscopic models. Meanwhile, intermediate students will be able to solve most typical questions on macroscopic models but can only be moderately successful on typical questions requiring microscopic models. These students will often fail on atypical questions on microscopic models. Only when students achieve expert level can they then solve problems designed with either of the models in all contexts and link types.

Following the designs discussed above, a test of knowledge integration in electric circuits (TKIEC) was developed, which contains 30 multiple-choice questions. The complete test is included in the Supplemental Material [54]. A summary of the design features is listed in Table I along

TABLE I. Question design for assessment of knowledge integration. The score patterns are predicted performance (L/M/H) for students at novice, intermediate, and expert levels of knowledge integration.

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

with the expected performance in scores from students at different knowledge integration levels. Here the expected scores are coded in terms of L/M/H for the low/medium/high performance and are in order of novice, intermediate, and expert levels. A pattern of MHH indicates medium scores for novice level students, high scores for intermediate level students, and high scores for expert-level students. Among these questions, some were adopted from DIRECT (Version1.0) [3], McDermott *et al.* [38], and Cohen *et al.* [27], which are marked with an asterisk (*) in Table I and listed in more details in the Supplemental Material [54]. The rest of the questions were designed by researchers of this study. These questions were selected and designed based on the need for specific contextual, conceptual, and structural features emphasized in Table I. All questions have been piloted and refined to address possible issues in contextual and structural designs. It is also noted that some of the more complex questions used a mixture of macroscopic and microscopic models due to the implementation of multilink or integrated-link features. The model-type classifications of these questions were based on whether the primary core concept used in a question is a macroscopic or microscopic model.

B. Data collection

The students involved in this research were in 11th grade from three average-ranking suburban high schools in China. These students have learned the physics content regarding basic macroscopic behaviors of circuits in simple parallel and series networks when they were in 8th grade. At the 11th grade, these students have learned all the topics in the conceptual framework including electrostatic field, electric potential and potential energy, more complex circuits, ideal and nonideal batteries, and microscopic models of electric current and resistance. These topics were taught in 20 lessons (45 min each) during a 5-week period. The assessment test was given at the end of their academic year as a post test. Students were allowed 40 min to complete the test, and most of them finished the test in the allotted time.

After testing, a total of 24 students were selected to conduct interviews. These students were selected from the three performance levels, with 8 students in each level, based on a score division of 0–40, 40–80, and 80–100 (in percentage) for their scores on the test. The interviews each lasted approximately 20 min, and the main purpose of the interview was to probe finer grained details of the students' thinking processes in solving circuit problems such as whether they applied any conceptual understanding or simply used memorization.

The quantitative and qualitative outcomes will aid to evaluate students' conceptual understanding in terms of their levels of knowledge integration by using the TKIEC test designed based on the conceptual framework established in part 1 of this research. The data analysis focuses on differences in student performances on questions with different design features discussed above. Statistical significances in comparing results of different question sets are determined using one-way ANOVA and further explored using t test and Cohen's d effect size. Interview data is used to further explore details of student reasoning and validate the conclusions drawn from statistical analysis.

C. Assessment properties of the test

The assessment was given to 590 students, out of which 586 valid data points were collected. The data were used to evaluate the assessment properties of the test including reliability, difficulty, discrimination, and point-biserial correlation (Pb-r). The reliability index of the test, which is commonly evaluated with the Cronbach's α, was found to be 0.738, indicating a good degree of reliability (>0.65) [55]. The overall difficulty and discrimination were found to be 0.517 and 0.374, respectively, which are also in the satisfactory regions [56,57]. The point-biserial correlations shown in the Supplemental Material also indicate good consistency between individual items and the overall test. Details of these statistical measures are listed in Table S1 of the Supplemental Material [54].

In addition to the classical statistics, the Rasch model has been widely adopted as an effective method to evaluate features of test items [58–62]. A unidimensional Rasch analysis of the TKIEC test data was conducted using the Winsteps package [59,62]. The results are included in Tables S2 and S3 in the Supplemental Material [54], which show good fitting and reliability of individual test items. In addition, the person-item map (Wright map) was used to show the distributions of person ability and item difficulty on a common vertical logit scale to compare if the distributions span properly over a wide range of ability and difficulty scales [63]. A proper distribution indicates an appropriate discrimination for students from various performance levels. The Wright map of TKIEC items is included in Fig. S2 in the Supplemental Material [54], which shows that the items span a wide range of difficulty levels across the logit scale (−2.53 to 1.84) and the students' estimated abilities are well distributed with near-normal forms across the range of the logit scale that matches well with the item difficulty levels. The results suggest that TKIEC establishes an appropriate discrimination for students from various performance levels. Altogether, the results of Rasch analysis demonstrate that the test items are reliable and present good coverage on the range of students' understanding of electric circuits.

D. Quantitative analysis of question designs

The overall mean score of the TKIEC is 51.71%, indicating an appropriate difficulty level for the students tested without concerns on ceiling or flooring effects. Details of student test scores on the questions categories designed with the three assessment features are listed in Table II. The measured outcomes are consistent with the expected student performances shown in Table I. For example, on questions designed with different link types, students perform best on single-link questions followed by multilink questions, and they have the lowest scores on integrated-link questions. A one-way ANOVA shows significant differences between the three question sets [$F(2, 1755) = 487.105$, $p < 0.001$], which are more clearly demonstrated with pairwise t tests between different question sets [$t_{\mathrm{SM}}(585) = 28.089$, $p < 0.01$, $d = 2.323$; $t_{MI}(585) = 13.980$, $p < 0.01$, $d = 1.156$; $t_{SI}(585) = 36.417$, $p < 0.01$, $d = 3.011$]. The results suggest that the link-type design provides a useful feature to measure students' knowledge integration, which has been shown effective in previous research [20].

On question sets designed with typical and atypical contexts, students scored significantly lower on atypical questions with a large score difference of 29.47% [$t(585) = 35.371$, $p < 0.001$, $d = 2.925$]. This result confirms that using contextual saliency in question design can provide a strong indicator to distinguish students at different levels of knowledge integration, which has also been demonstrated in previous studies [17–21].

Similarly, a large difference of 21.35% in mean scores is also found between question sets requiring macroscopic vs microscopic models [$t(585) = 27.202$, $p < 0.01$, $d = 2.249$]. This result confirms the predicted performances based on the conceptual framework model, which suggests that understanding microscopic models and the central idea is a key step in achieving an integrated knowledge structure in learning electric circuits.

As an exploration for finer-grained categories, the designs of link type and context can be combined to form four subcategories also shown in Table II. Notice that the possible subcategories of single-atypical and integrated-typical are excluded, since these types of questions are rarely used in instruction. The results indicate that the mean scores on the four subcategories are also distinctively different ($p < 0.01$ for pairwise t tests). Therefore, the subcategories can be used as a feature to further identify finer details of student knowledge integration.

Based on the analysis of students' performances discussed above, it is evident that the assessment design using link-type, context, and conceptual models can provide effective measurement for diagnosing different features of student knowledge integration. The features of link type and context have been shown effective in previous studies [17–21]. The use of microscopic (or mechanistic) models and macroscopic (or operational) models is a feature developed in this study, which can provide a new strategy for designing assessment of knowledge integration on topics involving the different forms of conceptual models.

Regarding the quantitative measures, it is also important to note the possible measurement uncertainties, which include several types. First, due to the nature of multiple-choice questions, there is a nontrivial probability for a student to choose a correct or incorrect answer by chance. In addition, the context dependence of learning also makes it likely for certain students, especially those at the intermediate level, to have mixed performances on questions designed for the same concept but with different contexts [25]. To address

TABLE II. Mean percentage scores ($N = 586$) on question categories designed with different configurations in link-type, context, and conceptual models. The mean scores are in percentage scale with standard errors shown in brackets.

						Concept	
#Q	Link type	Context	Link-context mean (SE)	Link type	Typical atypical	Macro	Micro
11	Single	Typical	70.01 (0.86)	70.01 (0.86)	66.44 (0.82)		
4	Multiple	Typical	56.61 (1.16)	46.40 (0.82)		61.67 (0.79)	40.32 (0.72)
7	Multiple	Atypical	40.57 (0.92)		36.97 (0.73)		
8	Integrated	Atypical	33.83 (0.82)	33.83 (0.82)			
30	Total mean: 51.71 (0.65)						

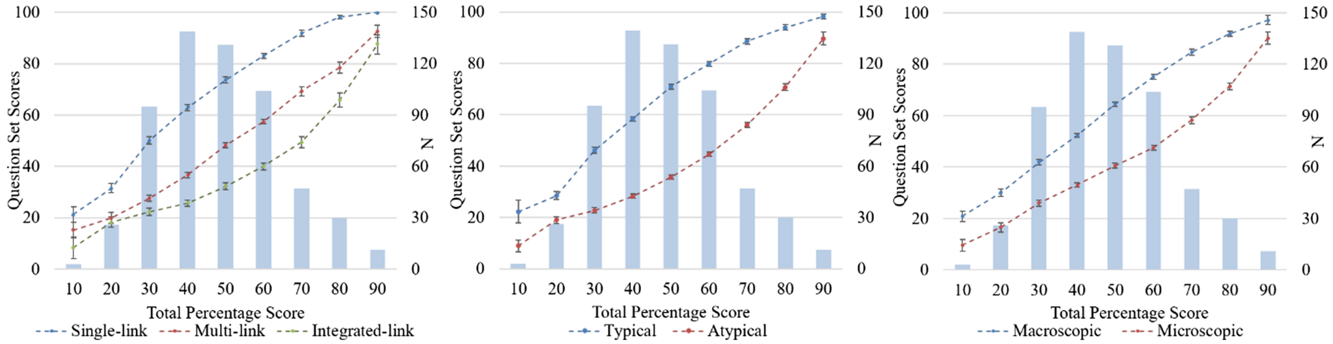

FIG. 2. Distribution of scores on question sets designed with different link types, typical vs atypical contexts, and macroscopic vs microscopic models from students at different total score. The histogram shows the frequency distribution of the students' total score on the test.

these issues, the questions need to be carefully designed, piloted, and refined to minimize random answers. It is also helpful to include multiple questions on the same concept and or knowledge construct (see Table I), which can lower the uncertainty due to random answers and the context dependence of understanding.

E. Quantitative analysis of students' knowledge integration levels

To examine how students at different overall performance levels may respond to the different question designs, the score distributions for the different question sets are plotted in Fig. 2. A histogram of total score frequency is displayed in the background to show the distribution of students across the different overall performances.

As shown in Fig. 2, scores on the question sets designed with the three different features show similar patterns, which are also similar to the results documented in previous studies [19,20]. The signifying feature of these diagrams is that the score differences among questions with different link types, typical vs atypical contexts, and macroscopic vs microscopic models are small at low total score (<40%). Students at this score range often perform similarly poor on all types of questions except for occasional success on single-link typical questions that target macroscopic models. These students are apparently at the novice level of knowledge integration and rely on memorization of equations and procedures in solving problems.

As the total score increases, performance gaps between the different types of questions within each design feature become more pronounced, showing that students in this range have started to perform well on simple and more complex typical questions requiring mostly macroscopic models but still have difficulties in solving atypical questions that target the microscopic models and the central idea. As the total score further improves, the performance on single-link typical questions quickly reaches the mastery level, and students' scores on multilink typical questions requiring macroscopic models start to show significant improvement. Meanwhile, the performances on questions designed with integrated-link atypical contexts and microscopic models also start to catch up. The results indicate that these students are at the intermediate level of knowledge integration who have developed partially integrated knowledge structures based on macroscopic models that link mostly typical contexts with some limited connections to atypical ones.

Finally, students with high scores (>80%) show a small difference between their scores on each of the three design features (see Fig. 2). In particular, these students are able to consistently solve most atypical integrated-link questions that target microscopic models, indicating that they have achieved a good understanding of the central idea with a well-integrated knowledge structure.

The score patterns on the questions designed with different features reveal a general progression of student knowledge integration that matches well with the novice, intermediate, and expert levels discussed in part 1 and summarized in Table I. Based on the conceptual framework model, students at the three levels of knowledge integration are expected to have different performances on questions with different designs of link structure, context saliency, and conceptual model. As indicated by the performance gaps among the questions with different designs shown in Table II and Fig. 2, the mean total score of the test can be a useful indicator for the different knowledge integration levels. Here a score division of 0–40, 40–80, and 80–100 (in percentage) is suggested for indicating the novice-intermediate-expert levels of knowledge integration and summarized in Table III. It is noted that since the knowledge integration levels are not independently determined with additional measures, and the assessment outcomes are population dependent, this specific score division scheme reflects only a reasonable approximation for the data in this study and should not be generally extended to other contexts and populations. Nevertheless, this work demonstrates the possibility for identifying a quantitative categorization scheme to model knowledge integration as well as its utility in teaching and learning.

TABLE III. Summary of total score and question set scores for each knowledge integration level. Standard errors are given in brackets. The p values reflect the significance of the one-way ANOVA analysis for the differences among mean scores of the novice, intermediate, and expert students in each question design.

Level (N)	Score range	Total score	Single	Multi	Integrated	Typical	Atypical	Macro	Micro
Novice (124)	0–40	31.72	45.53	25.66	21.07	41.83	21.61	38.86	23.56
		(0.50)	(1.41)	(1.02)	(1.22)	(1.19)	(0.93)	(0.98)	(1.01)
Intermediate (421)	40–80	54.31	74.43	49.02	33.91	70.89	37.72	65.31	41.74
		(0.48)	(0.77)	(0.75)	(0.81)	(0.71)	(0.64)	(0.70)	(0.63)
Expert (41)	80–100	85.45	98.67	82.26	71.65	95.12	75.77	93.29	76.48
		(0.91)	(0.60)	(1.93)	(2.69)	(0.84)	(1.77)	(0.96)	(1.75)
p value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

The quantitative results discussed above indicate that the assessment designs using different link types, typical and atypical contexts, and microscopic and macroscopic models are effective in measuring knowledge integration. The assessment results indicate that the majority of students were in the intermediate level of knowledge integration, where they had only achieved a basic level performance on the multilink typical questions but failed on most of the integrate-link atypical questions. The fact that most students performed rather poorly on the questions that require more than a single link is a clear indication of fragmentation within students' knowledge structures. The poor performances on questions requiring atypical contexts and microscopic models further reveal that most students lacked the understanding of the expert central idea. To further investigate finer grained details of student reasoning, interviews were conducted with students from each level of knowledge integration, which are discussed next.

F. Interview analysis of student reasoning pathways

From the same pool of tested students, a total of 24 students were recruited for interviews with 8 students from each level of knowledge integration. The levels of knowledge integration of these students were determined based on their total scores on the TKIEC following the score division of 0–40, 40–80, and 80–100 defined in the previous section. The interviews were conducted during the week after the students took the test. Students were asked to report their answers to the questions and explain their reasoning. The interviews were conducted for two purposes. One is to confirm if the quantitative assessment outcomes accurately reflect the actual student understanding and reasoning. The other is to verify if the knowledge integration levels determined by the total score of the test can produce correct categories consistent with the expected student behaviors outlined in the conceptual framework model in part 1.

The interviews were first transcribed and analyzed by two graduate students, which were further evaluated together with the faculty members to reach a consensus on the types of students' reasoning. This analysis focuses on coding and matching students' responses with the patterns of reasoning defined in the knowledge integration model. The results of interviews provide confirmatory evidence of the knowledge integration levels determined based on the quantitative data. Because of the small number of interviews conducted, the identified patterns do not imply any statistical significance. Nevertheless, the outcomes can provide teachers and researchers a possible landscape of student reasoning at different developmental levels.

1. Novice level

8 students from the total score range of 0%–40% were interviewed as the novice level sample. When taking the test, these students were able to correctly answer some typical questions. However, as revealed by interviews, most students' reasoning relies primarily on memorized equations and solutions of similar problems encountered before. For example, in answering Q1, a student stated: "*I have done a similar question before. The current in the series circuit tested is equal everywhere, so the currents at the two points are equal*."

Here, Q1 is a typical question that students have seen similar ones before. Therefore, using memorized equations and recalling results of similar questions can allow students to answer such typical questions correctly. However, these students were not able to provide further explanations on why the examples or equations could be used to answer the questions.

Beyond simple typical questions, using memorized equations often leads to incorrect answers. For example, Q15 is a typical question requiring some understanding of the microscopic model of current. A representative answer from students at this level states: "*This question seems to be using the equation of* $I = q/\Delta t$, *where* $q = 1.6C$ *and* $t = 1.0s$. *which gives the answer C*." Apparently, the student memorized the formula but did not understand the meaning of q should include both positive and negative charges. As a result, the calculation only considered the positive charges and ignored the negative charges. There were also students who even thought that the positive and negative charges should cancel each other. Such explanations indicate that these students lack a basic understanding of the central idea of how a current is formed.

On atypical questions, part of the context can look similar but with subtle differences that require the understanding of the central idea to correctly interpret. For example, Q17 is an atypical question on measurement of voltage, which requires the understanding of the relation between the potential difference and current. Students at the novice level usually fail on this type of questions, which is evident from the interview excerpt: "*This question seems to be the question that the open circuit voltage is equal to the power supply voltage, but the two points AB are not on both sides of the break point, and there is a light bulb in between, so the voltage divider should be considered, so choose C*." Apparently, this student recalled previous questions on measuring the voltage of batteries but failed to understand that since there is no current going through the light bulb, the potential difference between the two terminals of the light bulb should be zero. The voltage divider rule can only be applied when there is a current in the resistors in a series circuit.

The majority of students ($6/8$) at the novice level revealed reasoning patterns discussed above. However, a few students ($2/8$) also showed using blended intuitive reasoning to answer questions which could end up getting the correct answer occasionally. For example, on Q2 which is an atypical question on the macroscopic concept of parallel circuits, a student was able to select the correct answer of equal brightness (choice C) but with a reasoning based on inappropriate mapping and combination of circuit elements: "*Circuit 1 has one power supply for one light bulb. Circuit 2 has two power supplies for two light bulbs, which is equivalent to one power supply for one light bulb. So the bulbs are all equally bright in both circuits*." This is one example of very few cases of giving a correct answer based on incorrect reasoning. Most of the other students used some blended variations of intuitive and learned understandings and were trying to apply the ideas with a memorized equation, which led to incorrect answers: "*Circuit 1 has one power supply, which is a very simple circuit. Circuit 2 has two power supplies supplying voltage and current, which should be twice as much as circuit A. According to the formula* $\mathrm{P} = \mathrm{UI}$ calculation, *the power of the bulb in B is four times that of the A circuit. So the light bulb in circuit B is brighter and the light in circuit A is dimmer*."

In summary, as indicated from the interviews, students at the novice level can memorize equations and previously seen questions and apply them in limited familiar contexts but without a good understanding of the underlying concept. The strategy of memorizing equations usually fails on questions designed with microscopic models and atypical contexts, which is consistent with the quantitative assessment outcomes shown in Table III. The interview results further confirm that students at the total score range of 0%–40% behaved as the novice level defined in the conceptual framework model of knowledge integration.

2. Intermediate level

The intermediate level sample includes 8 students in the score range of 40%–80%. These students performed well on typical questions and demonstrated a good basic understanding of the microscopic current model. For example, in response to Q15, one of the student stated: "*This topic is mainly about the current and charge definition,* $I = q/\Delta t$. *In this case, because there are both positive and negative ions passing through the terminals in 1s, it is equivalent to the addition of two currents, which gives* $I = 3.2A$." Compared to the novice level, students at the intermediate level not only recalled the current-charge equation but also demonstrated a basic understanding of the microscopic model of the current being a flow of charges, which allows them to apply the model to both positive and negative charges and obtain the correct answer.

However, students at this level appear to lack the understanding of the relation between current flow and electric field (or potential difference), which is evident from a student's response to Q28, a question with a context that students have seen before but requires the understanding of the central idea that students at this level often failed to develop: "*This question is to examine the formula* $I = neSv$ *to determine the relationship between the current and the speed of electrons' movement. The question gives the speed of free electron movement and the length of the wire, which can calculate the elapsed time of current transfer. In the same way, when the switch is turned off, the current also needs time to pass, so choose E*." Apparently, the student was able to memorize the equation describing the current as a charge flow; however, this student did not seem to understand that the electric field is the driving mechanism underlying the charge flow. Without understanding that the electric field is established at the speed of light through the circuit, the student's model of the charge flow is a traffic queue process, which requires the charges from the power source to actually move to the light bulb for it to be lit up.

Besides the lack of a good understanding of the central idea, all of the intermediate level students also demonstrated some level of coexistence of correct and incorrect ideas. For example, on Q8, which requires the understanding of multiple aspects of the microscopic and macroscopic models of current and resistance, students at the intermediate level were often able to recall the relevant equations and demonstrate an understanding of the underlying concepts to a certain extent, but they would usually fail to correctly interpret the elements that are directly connected to the central idea: "*The resistance is given by* $R = \rho l/s$, *the length is equal, and they are all copper wires, which makes the* ρ *being the same. Then the resistance only depends on the cross-sectional area S. So, the ratio of resistors is* $3:2$, *and A is correct. Since the two are in series, the current is equal everywhere, and B is* *correct. Because the current is equal everywhere, the rate of movement of the electrons should also be the same, which should be 1*:*1, therefore, C is incorrect*." Here, the average speed of the directional motion of charges should be considered in relation with the current and cross-sectional area through the microscopic model described by $I = neSv$, which renders choice C being incorrect. The results suggest that this student had some understanding of the current being charges in motion, but without knowing the details of how the current and the average speed of the charges' directional motion are related.

As indicated from the interviews, it is obvious that the students at the intermediate level were able to understand some aspects of the microscopic models such as that the electric current is a charge flow; however, these students appeared to lack understanding of the central idea, which explains the electric field as the mechanism for driving the charge flow. Therefore, students at this level were able to correctly solve most typical questions requiring macroscopic models and can be occasionally successful on questions requiring a basic understanding of the microscopic models. But these students often failed to correctly solve atypical questions requiring the understanding of the central idea and the mechanistic aspects of the microscopic models. The interview results are consistent with the predicted behaviors of the intermediate level students defined in the conceptual framework model of knowledge integration, which further confirm that students at the total score range of 40%–80% can be categorized in the intermediate level of knowledge integration.

3. Expert level

The expert level sample includes 8 students in the score range of 80%–100%. All students at this level demonstrated a good understanding of the central idea and the related aspects of the microscopic models, which allows them to correctly solve most questions requiring microscopic models. For example, in response to Q28, an expert level student stated: "*Choose F. This question is actually not that difficult. After the circuit is closed, the power supply provides a potential difference. Under the action of the electric field, the free electrons in the entire circuit system all begin to have directional motion, which has nothing to do with the speed of the individual electrons*." Apparently, this student had a good understanding of the central idea, which explains the mechanistic aspects of the microscopic model of current, and was able to apply the central idea to a novel context and obtain a well-reasoned solution.

Based on the interview outcomes, a clear distinction between the expert and intermediate level students can be identified, which indicates that having a good understanding of the driving mechanism of the charge flow is the defining feature of the expert-level students. In contrast, the intermediate level students were able to understand the phenomenological behavior of current as charge flow but had not established the understanding of the deeper mechanism that explains the phenomenon. Lacking this essential mechanistic understanding, intermediate level students were only able to reason with phenomenological operations and procedures in problem solving, which often lead to failure in solving atypical questions requiring the understanding of the central idea. On the other hand, the expert-level students were able to apply their understanding of the central idea to questions designed with different contexts and models and solve these problems successfully. The interview results also confirm that students in total score range of 80%–100% have a good understanding of the central idea and can be categorized in the expert level of knowledge integration.

In addition, the interview results can provide useful implications to guide teaching and learning. As shown from the quantitative assessment outcomes, the majority of the tested students were at the intermediate level of knowledge integration after traditional instruction. This indicates that most students were not able to develop a sufficient understanding of the central idea, which calls for instructional interventions that can help students gain a deeper understanding of the mechanism underlying the electric circuits. It can be suggested that instructional emphasis should be made to help students establish the needed mechanistic understanding that the electric field is the driving mechanism of the electric current. Then the instruction can guide students to apply this understanding in different contexts to develop a well-connected knowledge structure.

IV. CONCLUSIONS

In this study, a conceptual framework model of simple electric circuits is developed and used to guide the assessment of students' knowledge integration in learning electric circuits. Following the conceptual framework model, a test on knowledge integration in electric circuits (TKIEC) is developed, which 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. Based on the analysis of assessment data and interview outcomes, the three assessment designs have demonstrated effectiveness in distinguishing students at different levels of knowledge integration, which are categorized into three developmental levels including novice, intermediate, and expert.

Students in the novice level had fragmented knowledge structures with little understanding of the central idea. In problem solving, these students demonstrated strong dependence on problem contexts, which were used to match memorized equations and previously seen examples. Using these strategies, the students were able to correctly solve some simple typical questions; however, they usually failed on more complex typical questions and the questions with atypical contexts. Interview outcomes further revealed that although these students might have memorized the related equations, they usually lacked the conceptual understanding underlying those equations. In particular, the understandings of the microscopic models were largely missing among these students.

Intermediate level students had started to develop a more connected knowledge structure with some basic understanding of the microscopic model of electric current flow, but the understanding was not connected to the concepts of electric field and potential difference, which form the driving mechanism of the current flow and an essential element of the central idea. Therefore, their knowledge structures were still locally organized among context features and intermediate procedures, which extend to most macroscopic models and some limited aspects of the microscopic models; however, these understandings were not connected to the central idea. In problem solving, these students still demonstrated significant dependence on using memorized equations and previous examples. They were able to correctly solve most typical questions requiring macroscopic models, but often failed on atypical questions requiring microscopic models.

Students in the expert level achieved a more integrated knowledge structure with a good understanding of the microscopic models and the central idea, which allowed them to apply these understandings consistently in both familiar and novel situations. Students at this level were able to correctly solve all typical questions requiring macroscopic models and most atypical questions requiring microscopic models.

Further analysis of the assessment results suggests that students' total test scores can be used as an indicator for their knowledge integration levels. This provides a convenient tool to inform instruction about unique learning aspects and problem-solving behaviors for students at different score range. For example, for students at the novice level, it would be useful to help them develop some initial understandings of the microscopic models and the central idea and make connections to the equations and problem-solving procedures which they usually attempt to memorize. For intermediate level students, instruction can emphasize the development of a more complete understanding of the central idea and related microscopic models as well as the applications of the understanding in atypical contexts.

In the recent studies on assessment of student knowledge integration using the conceptual framework model, a number of question design strategies have been gradually developed and tested, including content type [12,18], typical-atypical contexts [16,17,19], and link type [16]. In this study, a new method of using macroscopic and microscopic (or mechanistic) models is tested, which shows promising effectiveness in measuring student knowledge integration and can provide practical feedback to inform instruction. This new method can be a useful tool for assessment design on topics involving microscopic (or mechanistic) models.

Although encouraging outcomes have been observed, there are limitations to this research, which should be further examined in future studies. The population studied in this research has only a small number of low- and high-performing students, which limits the scope of the analysis on novice and expert-level students. It will be beneficial to study different populations with a large number of advanced students and/or low-performing students so that a more complete developmental progression of knowledge integration on electric circuits can be examined.

In conclusion, this paper documents a new application of the conceptual framework model to the topic of simple electric circuits and introduces a new assessment design feature using macroscopic and microscopic models of electric current. Guided by the conceptual framework, assessments were developed and tested. The results suggest that the design features of link-type, typical-atypical contexts, and macroscopic-microscopic models are effective in probing and categorizing student knowledge integration levels. The assessment outcomes also reveal that most students had only achieved the intermediate level of knowledge integration after traditional lecture-based instruction, which warrants future research on instructional interventions to improve student learning. Detailed analysis and comparisons of students' performances on the different types of questions provide useful implications for instructional design, which suggest that teaching the central idea and the related microscopic models in atypical contexts can be an important instructional strategy for promoting knowledge integration and deep conceptual understanding in learning electric circuits.

ACKNOWLEDGMENTS

The research is supported in part by the National Science Foundation Grant No. DUE-1712238, "Xing Fu Zhi Hua" Fund Pilot Project (Humanities and Social Sciences) "Research on system construction and innovative experiment of subject intelligence education" at East China Normal University (approval number: 2020ecnu-xfzh001), and the Postgraduate Project by the China Scholarship Council (No. 202106140073). 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.

Z. L. and S. P. contributed equally to this work.

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