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A Cross-Grade Study Validating the Evolutionary Pathway of Student Mental Models in Electric Circuits

Jing-Wen Lin
National Dong Hwa University, TAIWAN

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ABSTRACT
Cross-grade studies are valuable for the development of sequential curriculum. However such studies are time and resource intensive and fail to provide a clear representation to integrate different levels of representational complexity. Lin (Lin, 2006; Lin & Chiu, 2006; Lin, Chiu, & Hsu, 2006) proposed a cladistics approach in conceptual evolution to construct a hypothetical Conceptual Evolution Tree (CET; also called Evolutionary Pathway of Student Mental Models) in electric circuits which overcome the limitations of earlier cross-grade studies. The aims of this study are to validate this hypothesis and to integrate with the CET graph to better understand Taiwanese students' conceptual evolution in electric circuits. This study uses a web-based mental model diagnosis system to collect 1,441 cross-grade students' data. The results show that the empirical cross-grade survey data closely meet the hypothesis. The CET graph in electric circuits well explains the relationship between student conceptual evolution from Grade 1 to 9 and the curriculum influences by comparing to the empirical data. The validated CET graph in electric circuits could be a useful tool for science educators in designing sequential curriculum content.
Keywords: conceptual evolution tree (CET), conceptual change, cladistics approach in conceptual evolution, cognitive character, electric circuit

INTRODUCTION

Student preconceptions have been the focus of science education researchers for the last 30 years. Driver, Leach, Scott, and Wood-Robinson (1994) advocated using cross-age or cross-grade studies to understand the evolutionary process of student knowledge acquisition. The researchers of learning progressions pursued students' understanding changes as students come to develop sophisticated knowledge about big ideas in science (Stevens, Delgado, & Krajcik, 2010). According to the development of the conceptual sequence, these studies depicted the important step of knowledge development in their specific fields and provided more valuable information to curriculum designers by investigating students’ performances at particular ages. Pfundt and Duit (2009) collected a database of 8,338 relevant student conceptual studies. Despite this abundance of research, only 18 contained the words *cross age*,

Correspondence: Jing-Wen Lin, *National Dong Hwa University, Taiwan.*
jingwenlin@mail.ndhu.edu.tw

State of the literature

- Cross-grade studies are valuable for the development of vertical curriculum, but the limitations are time and resource intensive, facing validation problems and unable to provide a clear representation to integrate different levels of representational complexity.
- Researchers have implemented cross-age or cross-grade studies of students' alternative conceptions and mental models in electricity, but there is no survey to integrate different levels of representations in one study.
- The cladistics approach in conceptual evolution is an interdisciplinary innovation based on evolutionary epistemology and cladistics in biology. It can overcome the limitations of traditional cross-grade studies, but needs more empirical supports.

Contribution of this paper to the literature

- The proportional distribution of cross-grade survey validated the hypothesis of CET in electric circuits.
- The result of the cross-grade survey with the CET graph in electric circuits presents the distribution of students' alternative conceptions and mental models. It also explains Taiwanese Grade 1 to 9 students' conceptual evolutionary processes and the curriculum influences regarding electric circuits.
- Taiwanese curriculum guidelines generally parallel students' conceptual evolutionary processes in circuits. The learning progress of the revised sequential inference model, role of a bulb (pass/transmit), and revised source-consumer model is ahead of the evolutionary pathway prediction. Current conservation developed a little later than predicted.

across age, *cross grade*, or *across grade* in their titles. Relevant student scientific concept development studies were also scarce. The potential factors to influence the impact of these studies are time and resource intensive, and facing validation problems (Driver et al., 1994). Besides, this traditional approach only shows how *single* alternative conception develops and fails to provide a clear representation to integrate different levels of representational complexity (e.g. false beliefs, flawed mental models and incorrect ontological categories) (diSessa & Sherin, 1998; Gadgil, Nokes-Malach, & Chi, 2012). To address these limitations, Lin and colleagues (Lin, 2006; Lin & Chiu, 2006; Lin, Chiu, & Hsu, 2006) introduced the biological concept of *cladistics* to science education to develop a *conceptual evolution cladistics approach* which efficiently identified students' mental model evolutionary pathways. The core concept of *cladistics* is the use of derived characters to reconstruct common ancestry relationships and the grouping of taxonomic units based on common ancestry. This methodology promotes the tight connection between taxonomy and evolution and becomes a science discipline that can form hypotheses, test, and verify (Wiley, Siegel-Causey, Brooks, & Funk, 1993). In students' conceptual evolution, the taxonomic units are students' mental models (Lin, 2006). After deconstructing students' mental models in electric circuits (Chiu & Lin, 2005) into a matrix, Lin (2006) constructed a hypothetical evolutionary pathway of students' mental model via PAUP* 4.0 software, the most widely used package for phylogenetic inference (Netscape, 2016), and named it *Conceptual Evolution Tree (CET)* to stress the use of cladistics in biology in science education (will introduce deeply later)The CET in electric circuits provided a representation which integrated multiple kinds of misconceptions at different levels for interpreting student conceptual evolutionary processes and their interactions with the curriculum. Besides, it allowed different evidence (e.g., cross-grade surveys and transnational comparisons) to validate and revalidate this hypothetical pathway. Therefore, it can solve the validation problem better than traditional cross-grade or cross-age studies faced. Although this method appeared to introduce the advantages mentioned above, it had too few empirical validation sources and urgently required support, revision, or refinement from different studies and evidence sources. Therefore, this study validates the CET in electric circuits by conducting cross-grade study. To collect more data and allow younger students to understand question items more easily, a web-based mental model diagnostic (WMMD) system was developed (Wang, Chiu, Lin, & Chou, 2013). This system helped us to design dynamic representation questions to assist younger students in understanding test items more readily and enabled more efficient collecting and scientific analyzing of student alternative conceptions, mental models and evolutionary pathways. Comparing to the current curriculum guideline, this analysis helps us explain how curriculum influence students' conceptual evolution. Research results could be used for relevant curriculum and teaching design in primary school and junior high school.

STUDENT IDEAS OF ELECTRICITY AND RELATED CROSS-AGE STUDIES

Electricity is an important part of the science curriculum. According to Pfundt and Duit (2009), student concept studies of electricity or circuits were the second largest category after *force and motion*. Although researchers used different methodology and selected participants of different ages, all results indicated that students had considerably similar alternative conceptions (Arnold & Millar, 1987; Carlton, 1999). This is because electricity is an abstract concept and cannot be directly observed. After numerous alternative conception investigations, recent studies have tended to interpret student learning of electricity using a conceptual framework, for example, mental models.

What are students' mental models of simple circuits? Osborne and Freyberg (1985) investigated 8 to 12 year-old students' ideas of closeness in a circuit, bipolar circuit elements, and current direction. They defined four explanatory models: A. unipolar, B. clashing current, C. current attenuation, and D. constant current (scientific model). These models were also reflected in other countries (Butts, 1985; Gott, 1984; Shen, Gibbons, Wiegers, & McMahon, 2007; Shepardson & Moje, 1994; Shipstone, 1985). Based on previous studies, Magnusson, Boyle, and Templin (1997) divided the clashing current model into a cross current model, similar to the alternating current from two battery poles. The current attenuation model was divided into an attenuation model reflecting the uneven brightness of two light bulbs and a shared model reflecting the equal brightness of two light bulbs. The most detailed investigations on mental models of circuits were conducted by Chiu and Lin (2005). They examined the structure of and changes in student mental models when learning about circuit closed loop, bipolar circuit

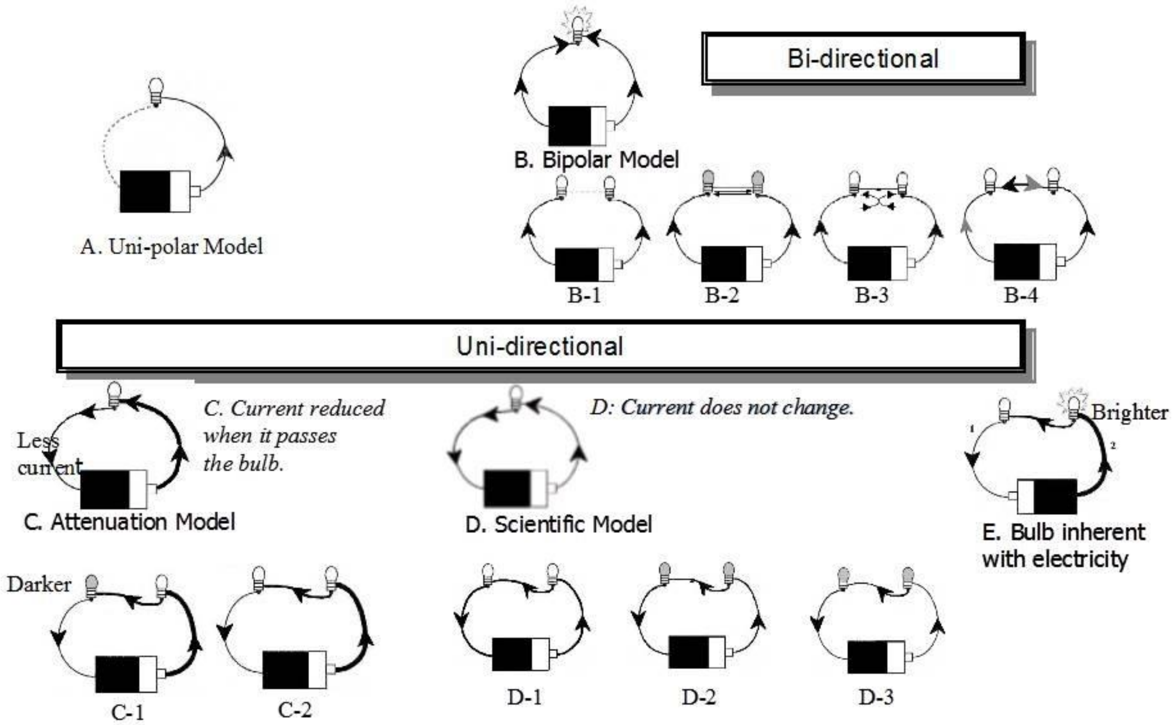


Figure 1. Students' mental models of electric circuit (revised from Chiu & Lin, 2005)

elements, current direction, and systemwide of circuits. Results showed that student performance on electric circuits could be categorized into five mental models and 11 subtypes (see **Figure 1**). The five mental models were A. unipolar, B. bipolar (or clashing current; with subtypes B1 to B4), C. current attenuation (with subtypes C1 and C2), and D. constant current (with subtypes D1 to D3), and E. the bulb itself has electricity. Lin (2006) deconstructed these mental models and identified 13 alternative conceptions from the literature review. These included: *the current between two bulbs*, *polarity*, *current direction*, *closed loop*, *the role of a bulb*, *current conservation*, *route*, *systemwide*, *sequential inference*, *source-consumer*, *bipolar elements*, *current and electric energy differentiation*, and *voltage conservation*.

Researchers have implemented cross-age or cross-grade studies in electricity since the 1980s using paper-pencil tests, experiments, and interviews (Dupin & Johsua, 1987; Osborne, 1983; Osborne & Freyberg, 1985; Tasker & Osborne, 1985). Their results showed that younger students tended to use the unipolar model, and the clashing current model was commonly used by students up to 13 years of age. With greater age, teaching, and learning interactions, the number of students using the scientific model also increased, but this had little effect on the current attenuation model (Borges & Gilbert, 1999; Chiu & Lin, 2005; Osborne & Freyberg, 1985; Shen et al., 2007; Shipstone, 1984, 1985). Many researchers have stated that students tend to use the current attenuation model because of the influence of the source-consumer and sequential inference models. When students use the source-consumer model, they think that a battery is a unipolar provider and that electricity or an energy storage tank provides current but not voltage in a circuit (Psillos, Koumaras, & Tiberghien, 1988). Students who use the sequential inference model think that current is gradually consumed and returned to the battery after electricity leaves the battery and moves through elements. This process is similar to a series of events in the circuit (Closset, 1983; Shipstone, 1984). In summary, the study of mental models in electric circuits has received much attention and has accumulated several common and stable mental models. Building a hypothetical CET begins from selecting appropriate mental models (Lin, 2006). Therefore, this study selected this topic to conduct the cladistics analysis and for easy comparison of the study results with the extensive literature.

STUDENT CONCEPTUAL EVOLUTION APPROACHES IN SCIENCE

There are three approaches to analyzing student concept evolution in science: cross-age or cross-grade investigations, learning pathway investigations, and the cladistics approach in conceptual evolution (Chiu & Lin, 2008).

A cross-age or cross-grade investigation is usually a large-scale study that examines the process of student conceptual development to provide appropriately designed curricula to students of different ages. However, it is time and human resource intensive. The 2003 National Science Concept Learning Integrated Project supported by the Taiwanese National Science Council was a large-scale cross-grade study. For 6 years, resources were invested to investigate nearly 10,000 Taiwanese primary to senior high school students' development and sources of concepts in physics (including electricity), chemistry, and biology using two-tier diagnostic items (Chiu, Guo, & Treagust, 2007; Lee, 2007; Tsai, Chen, Chou, & Lain, 2007). This type of large-scale national project was unique; therefore, the *International Journal of Science Education* published the results in a special issue. Unfortunately, the results of these surveys were *descriptive* in nature, and only focused on each single alternative conception; thus, the contributions for curriculum design were limited.

The study of learning pathways states that learning is the self-development of the cognitive system (Niedderer, 1997). Accordingly, learning is the construction of new cognitive elements and the change of cognitive attributes. This approach usually focuses on specific or a small number of students, follows their concept development over several weeks of lessons, and carefully analyzes their learning pathways to evaluate the validity of the teaching-learning sequence. It is difficult to quantify learning pathway studies, and only certain circumstances allow researchers to examine, test, and discuss the validity of student learning pathways (Méheut & Psillos, 2004).

The limitations of cross-age or cross-grade studies and learning pathway investigations were listed above. The cladistics approach in conceptual evolution was proposed to address these disadvantages (Lin, 2006; Lin & Chiu, 2006).

CLADISTICS APPROACH IN CONCEPTUAL EVOLUTION AND ITS PREDICTIONS ON THE EVOLUTIONARY PATHWAYS OF STUDENTS' MENTAL MODELS

The cladistics approach in conceptual evolution is an interdisciplinary innovation based on evolutionary epistemology (Campbell, 1974; Hull, 1988; Toulmin, 1972) and cladistics in biology (Wiley et al., 1993). For example, the *cognitive character* (C-character) stands for a special kind of concept—including scientific concepts as well as the important, robust, and common alternative conceptions in students' mental models (Lin, 2006), and it maps to *everything in the scientific enterprise* (including theories, concepts, and the meaning of language) in evolutionary epistemology and genes in biology. *New information learning* in student concept learning, maps to *innovation* of Toulmin's evolutionary epistemology and *random genotype and phenotype variations* in genetic cladistics.

A detailed analogy of different levels of the evolutionary perspective is found in the Lin's (2006) study. The conceptual evolution cladistics methodology begins with a complete investigation and precise coding of student mental models. With the assistance of cladistics software, in a short time this approach identifies the hypothesis and characteristics of student mental model evolutionary pathways on specific topics. The C-characters clearly show student learning difficulties, concepts interaction and developments for specific topics. This allows relevant experiments to be designed to support, revise, or reject a hypothetical pathway to make it a more scientific, systematic, and less resource-intense approach. However, using these analogies in an educational context has restrictions. Lin (2006) indicated that the biggest restriction is that biological evolution follows natural laws, but student mental model evolution is directional and is directed to scientific models (usually contemporary scientific paradigms) recognized by textbooks. This restriction is actually an advantage because researchers can use computers to predict most students' mental model evolution tendencies, thus contributing to curricula and teaching material design. Lin also indicated that more restrictions to the evolutionary epistemology and cladistics approach probably exist, depending on science education researcher understandings of the nature of student scientific concepts. If the nature of student concepts is better understood, the advantages and restrictions of combining student concept learning, evolutionary epistemology, and biological evolution will be better understood.

For the cladistics approach in conceptual evolution, if researchers use student mental models of internationally common topics, the results are applicable to many students. By contrast, if mental models of specific participants are used, the results only represent the possible pathways of specific students (Lin, 2006). The first topic applied to this novel approach was *electric circuits*. This is because the study of mental models of circuits is one of the most completely investigated topics (Pfundt & Duit, 2009), and its types of mental models are quite common and stable in different countries (Chiu & Lin, 2005; Osborne & Freyberg,

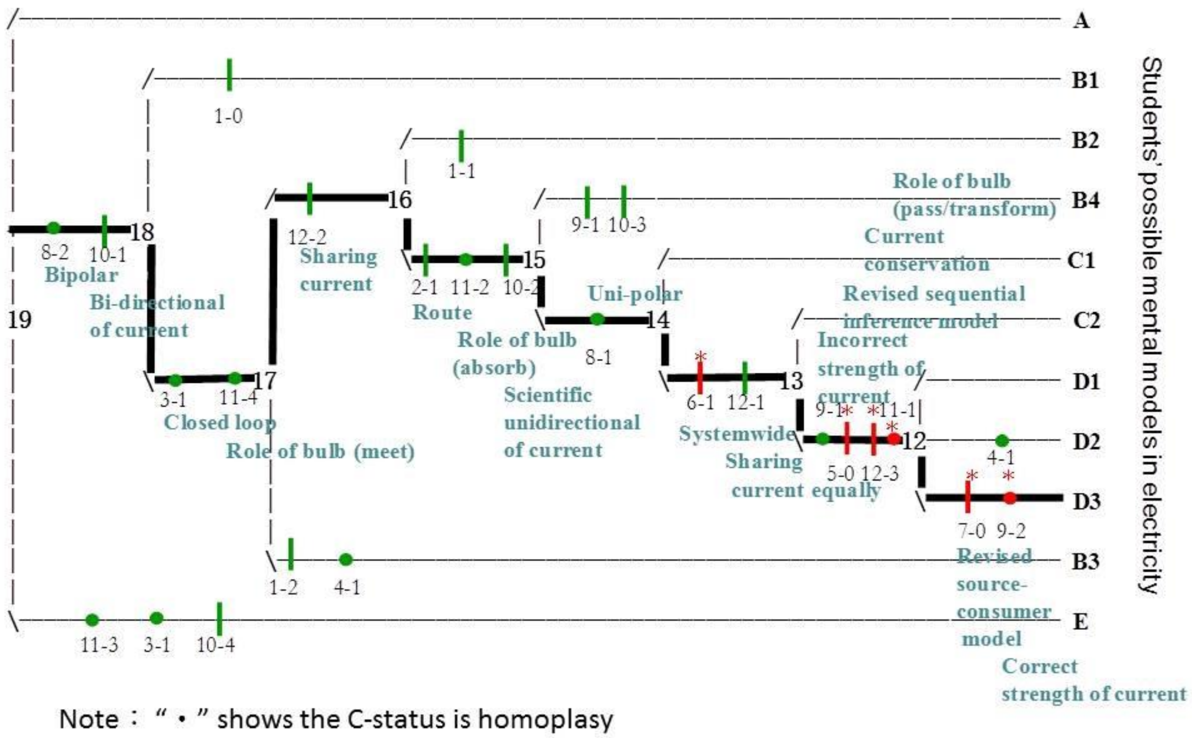


Figure 2. The hypothesis of the evolutionary pathways of students' mental models in electric circuits

1985; Shipstone, 1984, 1985). The result of this research has implications for both local and international students.

After searching the ERIC and Academic Search Premier databases and the bibliography created by Pfundt and Duit (2004), Lin (2006) found that Chiu and Lin's study (2005) covered the relatively complete and detailed types of mental models in electric circuits. Lin deconstructed 11 electric circuit mental models and 12 C-characters from Chiu and Lin, developed coding for them, transferred them into a matrix using Bioinformatics PAUP* 4.0 software, and established the possible hypothetical CET in electric circuits according to phylogenetics judgment rules, such as *inclusion/exclusion rule, and rule for determining relative derived character*. These possible CET were evaluated by the criteria of parsimony (Wiley et al., 1993). At the last step, the best phylogenetic trees were selected by the research results of previous science education literature reviews (Chiu & Lin, 2005; Osborne & Freyberg, 1985; Shipstone, 1984, 1985). For a detailed description of this method, see Lin (2006), Lin & Chiu (2006). **Figure 2** shows the final results.

Considerable information exists on the representation of the CET in electric circuits. This information can be used as a design reference. The right side of **Figure 2** (A, B1, B2, and so on) represents the 11 electric circuit mental models from Chiu and Lin (2005). D3 is the scientific model. Because science teaching is directional, the construction of student mental models should begin at the *Root* (Node 19). C-characters are gradually added and revised, which results in the scientific model. In the CET in electric circuits, the thick line shows the pathway. In the number pairs on the lines, the first number represents a C-character, and the second number represents the different statuses of the specific C-character. In Lin's studies (Lin, 2006; Lin & Chiu, 2006), the C-characters indicate important electric circuit concepts and alternative conceptions that are difficult for students to understand. Because each C-character includes scientific concepts and students' various alternative conceptions, different statuses are encoded. For example, *8-2* at the bottom of CET in electric circuits indicates the eighth C-character and the second cognitive status (C-status, it means different types of a C-character). As described in the original coding table (Lin, 2006) and in the results section below, the eighth C-character is the *polarity* of a battery, and the two C-statuses of this character are 8-1 (unipolar) and 8-2 (bipolar). Of them, 8-1 is the scientific concept, and 8-2 is an alternative conception. The hypothetical pathway leading to the scientific model is as follows: *Root→ polarity (8-2, incorrect, bipolar), current direction (10-1, incorrect, bi-directional current) → closed loop (3-1), role of a bulb (11-4, incorrect, meet) → distribute current (12-2) → route (2-1), role of a bulb (11-2, incorrect, absorb), scientific unidirectional current (10-2) → unipolar (8-1) → system wide (6-1), current sharing (12-1) → incorrect current strength (9-1), revised sequential inference model (5-0), current conservation (12-3), role of a bulb (11-1, correct, pass/transform) → revised source-consumer model (7-0), correct current strength (9-2).*

This pathway predicts that students initially use the concept of a bipolar battery (8-2), and that they believe that bidirectional currents (10-1) meet in the bulb (11-4) and shine. In addition, for the bulbs to shine, the bulbs, wire, and battery should be a closed loop (3-1). Most students use the idea of current distribution to the two bulbs and tend to believe that the bulb that first encounters the current absorbs more current (12-2) and the circuit then becomes a route (2-1). Students also use the idea of unidirectional current (10-2) and no longer believe that the bulbs shine because the bidirectional current meets in the bulbs. The route and unidirectional current concepts follow the concept of current absorption making bulbs shine (11-2). Subsequently, students may revise the C-status of unipolar batteries (8-1). Students then tend to believe that the two bulbs share the current equally (12-1), and therefore, have a better understanding of the whole system (6-1). Students gradually overcome the sequential inference model concept (5-0), revise their concept of incorrect current strength (9-1), understand that electric energy can transform to light and heat to make a bulb shine (11-1), and understand current conservation more (12-3). Students can then understand the role of voltage and, because they do not use the source-consumer model (7-0), they can understand current strength (9-2). The end of the pathway indicates later additions and revisions; therefore, these are the most difficult concepts for students to learn or overcome. In **Figure 2**, the most difficult concepts are the source-consumer model, incorrect current strength, the sequential inference model, current conservation, and current and electric energy differentiation.

The representation of the CET in electric circuits predicts the process of student conceptual evolution and shows the complex relationship between concepts and alternative conceptions. For example, there are three C-characters—route (2-1), role of bulb (11-2, incorrect), absorb (10-2)—between Nodes 15 and 16. This implies that the bulb absorbs current and then shines, reflecting scientific unidirectional current (10-2). These three C-characters are classified on the same internode. This indicates that they influence each other. In other words, when teachers teach the correct route and current direction, if instruction is not specially designed, students can easily formulate an alternative conception, such as the bulb absorbing current. Heller and Finley (1992) and Shipstone (1984) also reminded teachers to note this when teaching electricity. When using the cladistics approach, Lin and colleague did not use empirical methods, but predicted the complex interaction between concepts mentioned in the literature (Lin, 2006; Lin & Chiu, 2006). Therefore, this approach requires more empirical support, revision, and refinement. To validate the CET in electric circuits, Lin and Chiu (2007, 2009a) designed a set of diagnostic test items to investigate 440 students from Grades 3 through 9 to obtain cross-grade percentages for C-characters and C-statuses. This was the first validation of the CET in electric circuits. Results showed that most predictions came close to fitting the empirical data, except C-character 12. C-characters 12-1 (two bulbs share current equally) and 12-2 (two bulbs share current unequally) are important alternative conceptions (Chiu & Lin, 2005; Magnusson et al., 1997), but their percentages in cross-grade survey were too low (5% to 15.8%). Because this result was not identical to other results, Lin and Chiu (2009a) suggested that the cross-grade survey items should be revised. The first validation study mostly verified the feasibility of applying the evolutionary pathway cladistics approach, the CET in electric circuits, to student mental models in electric circuits.

Curricula and teaching material design are not a simple collection or arbitrary presentation of knowledge. They must follow the development of student cognition. Therefore, conceptual evolutionary pathway investigations are important (Driver et al., 1994). Previous cross-age or cross-grade studies have shown student metal models of circuits, how *single* alternative conceptions develop, and alternative conceptions that are difficult for students to revise when learning concepts. However, these studies are time and human resource consuming or lack quantitative evidence. Furthermore, few of these studies have been conducted, and they lack direct connections to the curriculum; therefore, it is difficult to use them for curriculum suggestions. The cladistics approach in conceptual evolution combines the advantages of cross-age and cross-grade studies and learning pathway studies. It can provide an overview of student conceptual evolution trends, and examine the *complex relationship* between the evolution of student mental models and their concepts at a specific stage. Therefore, this approach seems to solve the conceptual evolution research methodology limitations. This innovative approach focuses on the clear interpretation and explanation of theories and most importantly it provides further evidence from empirical studies. This study not only includes a cross-grade survey to validate the CET in electric circuits, but also serves as an example for integrating with the CET approach to better understand Taiwanese students' conceptual evolutionary processes regarding electric circuits. It displays how this approach overcomes the limitations of cross-age and cross-grade studies and the disadvantages of linking curriculum to examine the feasibility of this interdisciplinary approach. The research questions are as follows:

1. What is the percentage distribution of third, fifth, seventh, and ninth graders' C-characters for electric circuits?
2. Does the prediction of the CET in electric circuits correspond to the percentage distribution of the third, fifth, seventh, and ninth graders' C-characters for electric circuits?
3. What is the relationship between the percentage distribution of the third, fifth, seventh, and ninth graders' C-characters for the electric circuit and the curriculum?

METHODOLOGY

Previous literature did not distinguish between cross-age and cross-grade studies. However, this study is defined as a cross-grade study because participants were selected according to their grade and not their age. This was because cross-age studies tend to relate to the cognitive development of participants, and cross-grade studies focus on exploring the acquired curriculum of participants and how environmental factors affect conceptual evolution. This study focuses on how the curriculum influences student conceptual evolution; therefore, it is a cross-grade study.

Participants

Participants in this study were 1,441 students from grades 3, 5, 7, and 9. These grades were selected because, according to the Grade 1 to 9 Curriculum Guidelines in Taiwan (Ministry of Education of Taiwan, 2003; see **Table 1**), students before grade 3 are not taught any circuit concepts. In grade 4, some teaching is related to circuits, and in grade 6 teaching focuses on electric motors, conductors, and energy conversion. The grade 6 curriculum is not directly related to circuits, but is still relevant to the concept of electricity. At the beginning of grade 9, most textbooks teach students the relationship among voltage, current, and resistance in a circuit. Student concepts related to electrical circuits can be thoroughly examined following teaching in grade 9. These selected grades reflect the beginning or intervention of the curriculum. The interval between grades is 2 years to assist in examining how curriculum and age influence the evolution of student C-characters.

To select participants, a large primary and junior high school in Taipei was selected. The socioeconomic status of parents whose children attend these schools was median. After explaining the purpose of the study to the administrative staff, the staff identified classes that were willing to participate in the study. Four primary schools and two junior high schools participated. Fewer grade 9 students participated in this study because these students had to complete national entrance examinations and teachers believed that it would be difficult to participate in the study and prepare for the examinations. **Table 2** shows the participant distribution.

Table 1. Grades 1 to 9 curriculum guidelines for science and technology in Taiwan

Grade	Subtopic	Content
Grade 4	Electromagnetic effect	Use wires, batteries, or metal materials to connect a route and make bulbs shine or motors move.
	Electricity and its application	Use wires and batteries to connect a route and make a toy motor move.
Grade 6	The type and transformation of energy	1. Solar energy can make the water temperature rise (become hot) and can generate electricity. 2. The deflection of the compass is the result of the interaction between magnetic needles and magnetic field.
	Electricity and its application	Understand the electric conductivity, and the ways to avoid dangers of electricity.
Grade 9	Electromagnetic effect	1. Discuss electrostatic phenomena (e.g., triboelectricity and electrostatic induction). 2. Ohm's law. Discuss the relationship between voltage, current and resistance in the circuit.

Table 2. The distribution of the participants

Grade	3rd	5th	7th	9th	Total
Classes	14	16	10	6	46
Students	432	482	350	177	1441

Instruments

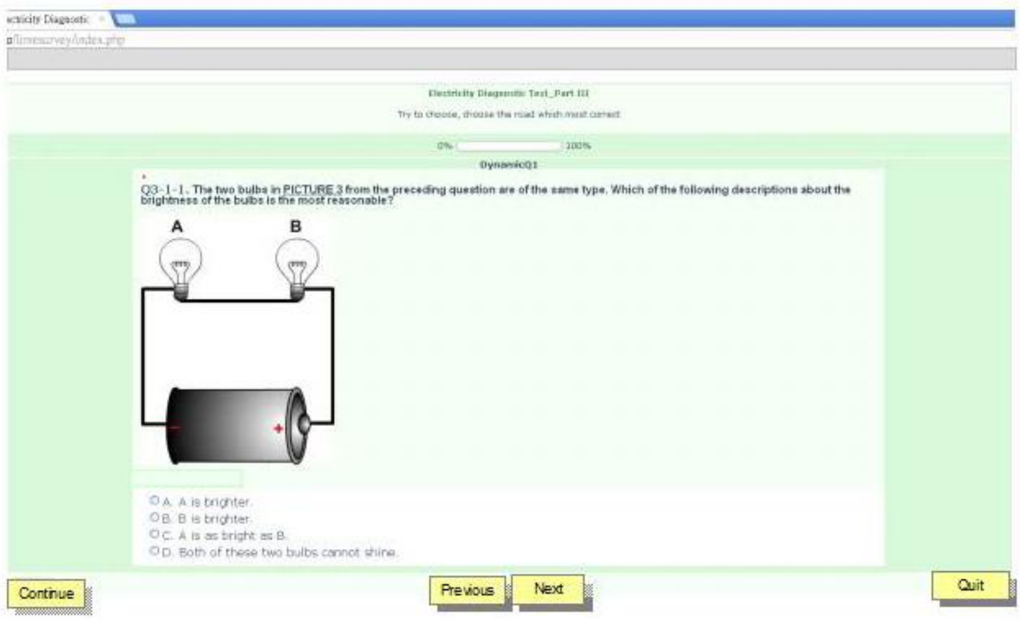
This study revised a circuit diagnostic test (Lin, 2006; Lin & Chiu, 2007, 2009a) to investigate the C-character evolutionary processes of student mental models of circuits across grades. The original test was based on the 13 alternative conceptions of mental models of circuits and used the coded C-character statuses and important alternative conceptions from the literature as options or questions. However, developing items appropriate for grades 3 through 9 was difficult. Ten C-characters related to the CET in electric circuits are found in Lin (2006): 1.current between two bulbs, 2.route, 3.closed loop, 5.sequential inference, 6.system wide, 7.source-consumer model, 8.polarity, 10.current direction, 11. role of a bulb, and 12.current conservation (the numbers are C-character codes). The empirical data for C-character 12 did not match the CET in electric circuits prediction or the literature review (Lin & Chiu, 2009a). Therefore, the original version was improved and items unrelated to the CET in electric circuits (e.g., *bipolar of elements*, *current and electric energy differentiation*, and *voltage conservation*) were deleted. **Table 3** shows the items of the revised version. Because only 10 C-characters were investigated, the research results could not be over inferenced.

Table 3. Item list of diagnostic test in circuits in this study

Code	C-Character	Definition for Scientific C-status	Items										
			1.1	1.2	2.1	2.2	2.3	3.1	3.2	3.3	3.4	4.1	4.2
1	Current between two bulbs	There is current between two bulbs in series connection and the direction of current is correct.		√				√					
2	Route	Current starts from one end of the battery, goes through the circuit element, and back to the battery to make a route.	√	√				√	√				
3	Closed loop	The wire, power, and electrical appliance are connected to make a closed loop.	√	√				√	√				
5	Sequential inference model	Students think electricity flows from the battery through the circuit elements and then turns back to the battery just like a series of events. They solve circuit problems according to this incorrect inference. Students did not use this model in scientific thinking.							√				
6	Systemwide	Systemwide point of view toward circuit.						√	√				
7	Source-consumer model	The battery causes potential difference and drives charged particles to move in the wire.								√		√	
8	Polarity	Current starts from the positive pole, not both positive and negative poles.		√				√	√				
10	Scientific unidirectional current	The direction of current starts from the positive pole of the battery and goes through the circuit element and finally comes back to the negative pole.		√				√					
11	Role of a bulb (electric resistance)	The bulb transforms electric energy into light and heat and then shines. The bulb does not block or absorb current and then shines.						√					√
12	Current conservation	Current is the movement of electric charge. Because of charge conservation, current is consistent and will not decrease.			√	√	√	√			√		

The diagnostic test (**see Appendix**) has four parts to examine students' conceptual learning. The first part is drawing. Students must decide if the bulb in the circuit shines and then determine if current runs through it. If they think there is current, they must draw the direction of the current (**see Appendix part I**) (the drawing of simple circuit is worth 4 points, while the drawing of series circuit is worth 6 points). The second part is on current conservation. Students must compare the current intensity of different circuits (each answer is worth 2 points). The third part is a two-tier diagnostic item (Haslam & Treagust, 1987; Peterson, Treagust, & Garnett, 1989; **Figure 3**). The first tier presents phenomena and the second tier presents reasons for these phenomena (each tier is worth 2 points). The last part consists of multiple-choice questions to test the students' concepts regarding the *source-consumer model* and the *role of the bulb* (each answer is worth 2 points). The multiple-format design was based on student interviews from Chiu and Lin's (2005) study. Because this study

Step1. The first tier (2 points)



Step2. The second tier

If someone chooses A, then second tier items of A appear. If someone wants the animation to assist with item understanding, the student can click on "Click here to see the animation," and the animation window pops up. (2 points)

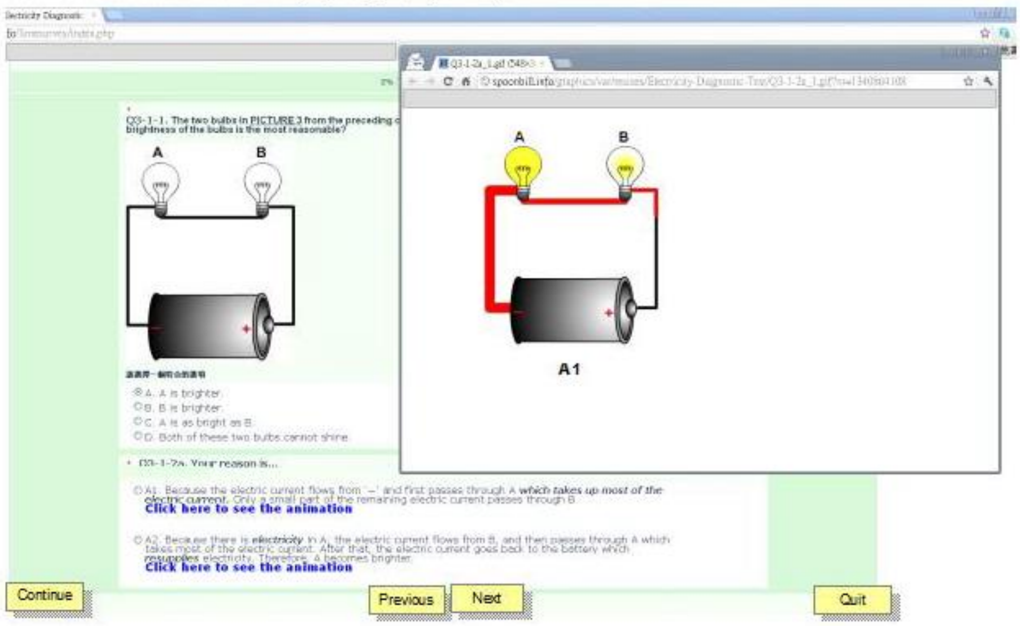


Figure 3. The example of Part III items (two-tier diagnostic item)

requires large-scale diagnostics of students' alternative conceptions, suitable question formats were designed according to the nature of these alternative conceptions.

Validity

Because the designed items should be appropriate for grades 3 through 9, follows were our efforts to improve the face validity: (1) Based on the reading level of primary school students, all characters in the primary school test were written with mandarin phonetic symbols. (2) The WMMD system presented conditions for questions based on students' earlier answers and inserted animations to help students visualize current direction options (Wang, Chiu, Lin, & Chou, 2013; **Figure 3**). (3) The interview was conducted and the diagnostic test with item confidence was designed to diagnose 331 third graders' and 335 fifth graders' adequate understanding, guessing, knowledge deficiency, or alternative conceptions. The results showed the younger students' correct answers are mostly adequate in understanding, but incorrect answers are alternative conceptions (Lin & Wu, 2013). It also confirmed the designed questions and formats could almost accurately reflect younger students' understanding.

After revising the instrument, three physics and science education professors and two junior high science teachers provided advice, corrected the test content, and compared it to the previous version.

Reliability

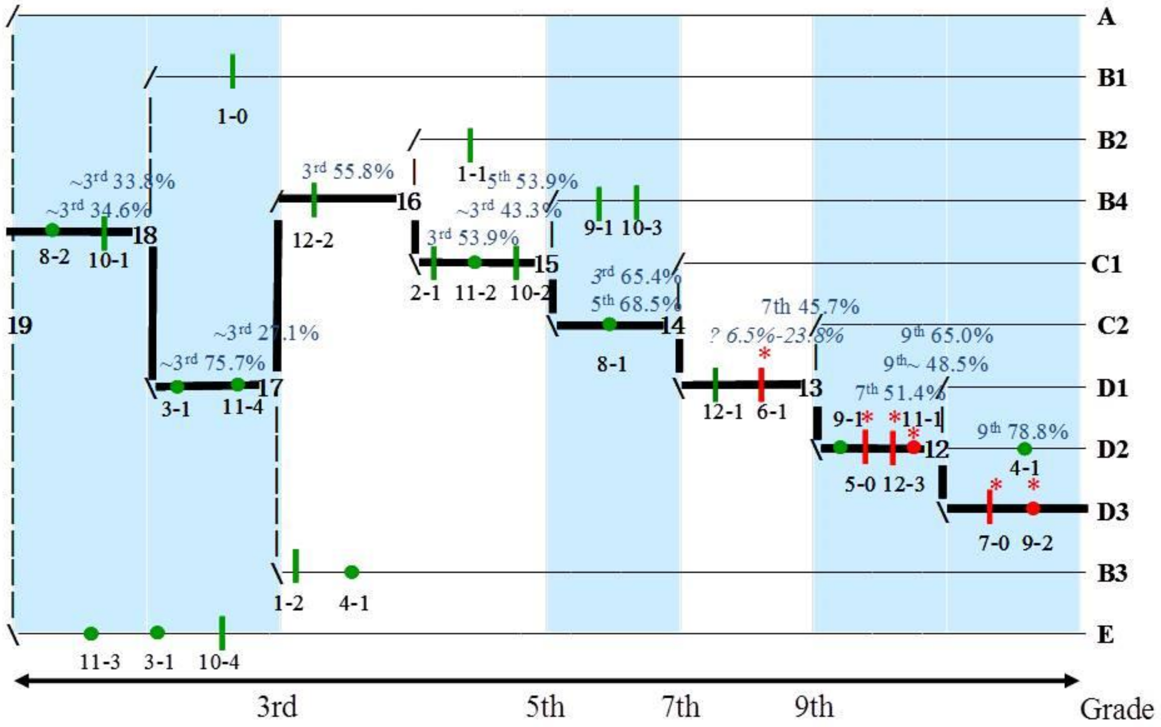
The revised instrument was also piloted using the WMMD system by 33 ninth graders from a high school, 37 seventh graders from a junior high school, 33 fifth graders, and 30 third graders from an elementary school in Taipei. The test-retest reliabilities (the interval was two weeks) were 0.77 for grade 3, 0.83 for grade 5, 0.82 for grade 7, and 0.89 for grade 9. Cronbach's α for the diagnostic test was 0.60 for grade 3, 0.68 for grade 5, 0.68 for grade 7, and 0.71 for grade 9.

Data Analysis

Based on the research purposes, data analysis was divided into three parts:

Percentage distribution of cross-grade C-characters

The percentage of C-characters was calculated according to the student selection ratio in the diagnostic test. Two types of analysis were used: one item for a C-character and several items for a C-character. For the first type, C-character 5 (*sequential inference model*) was used as an example (see **Table 3**). Its related item is only 3.2, and each option represents one student's understanding of this C-character. Therefore, the percentage of selected options was used to calculate the final ratio of each status. For the second type, C-character 7 (*source-consumer model*) was used as an example. Items related to this C-character are 3.3 and 4.1 (**Table 3**). Therefore, the final ratio of each status is the average percentage of each C-status for the two items.



Note：1."?" indicates the result and the prediction of the empirical study did not match well.
2. The code of "~3rd" implies the prediction of Tree 70 may be verified "before" the 3rd grade;
the code of "9th ~" implies the predication of Tree 70 may be verified after the 9th grade.

Figure 4. Analysis graph of students' mental models evolutionary process of C-characters in electric circuits

Validation of the hypothetical CET in electric circuits from cross-grade survey

The CET in electric circuits was validated by investigating whether the timing of C-statuses matched its predictions. Rules were based on Lin (2006) and Lin & Chiu (2007, 2009a):

1. Consider the first ranking of each C-status in a C-character. The "first rank" C-status implies it is the most dominate concepts in the surveyed grade.
2. Confirm whether the student C-status frequency is over 50%. If not, the upward or downward frequency trend may have reached 50% during a stage that was not investigated, and the timing of a specific C-status must be decided. Setting up "50%" just because this number could represent most students' concepts.

The relationship between student conceptual evolution and the current curriculum

This study used the chi-square test for homogeneity to test the differences between grades. This method assists in deciding C-status timing and clarifies the student conceptual evolution relationship. A Z test was used as a post hoc comparison to identify the differences between grades. If there is a statistic difference, it might result in the influence of curriculum. We examine the Grade 1 to 9 Curriculum Guidelines in Taiwan further to check the relationship between student conceptual evolution and the curriculum.

RESEARCH RESULTS

The results of percentage distribution of cross-grade C-characters were integrated with the CET in electric circuits (see **Figure 2**) to create an analysis graph of student C-character mental model evolutionary processes of electric circuits (see **Figure 4**). The graph enables the hypothetical CET in electric circuits prediction to be compared to the empirical investigation and be validated. This action also takes previous, traditional cross-grade studies step further. It makes the descriptive in nature of pervious methodology to change into explanatory, and single alternative conception surveys change into the investigation of the interaction between several concepts.

As for the validation, in principle, the proportion of students with C-characters close to the beginning of the CET in electric circuits should be above 50% when students are in grade 3 or below. As the grade increases, if the C-character conforms with scientific concepts and has been taught to students, the proportion should increase. By contrast, as the grade increases, if the C-character is an alternative conception, the proportion should decrease. C-characters in the middle of evolutionary pathways should be close to 50% in grades 5 and 7. For C-characters at the end of evolutionary pathways, the proportion could reach 50% by grade 9 and above. The following section reports the percentage distribution of each C-character (research question 1) and examines the relationship between the cross-grade C-character survey and the curriculum (research question 3), and the validation of the CET in electric circuits (research question 2). For convenience, the C-characters in the empirical investigation are reported and validated in the order shown by the thick line in the CET in electric circuits (except C-character 1 for it is not in the thick line).

C-character 8—Polarity

This C-character refers to the polarity of a battery and has a *unipolar* (8-1) and *bipolar* (8-2) status. *Unipolar* is a scientific concept that means that current flows from the positive pole of a battery. *Bipolar* means that current flows from the positive and negative poles. **Figure 5** shows that the distribution of each C-status in each grade is significantly different ($\chi^2_{(3)}$= 339.955, p = .000). The post hoc comparison indicates that the unipolar C-status (8-1) increases significantly from grades 7 to 9 (69.9% to 92.2%). In the current curriculum, circuit concepts are taught in grade 4 and at the beginning of grade 9. Therefore, the distribution of this C-character should increase significantly from grades 3 to 5 and grades 7 to 9. The data only confirmed that this occurred from grades 7 to 9. However, the CET in electric circuits analysis showed that this C-character was a similar character that is shared by two mental models (it also called homoplasy in cladistics) **(Figure 4**), which implies that the scientific model of

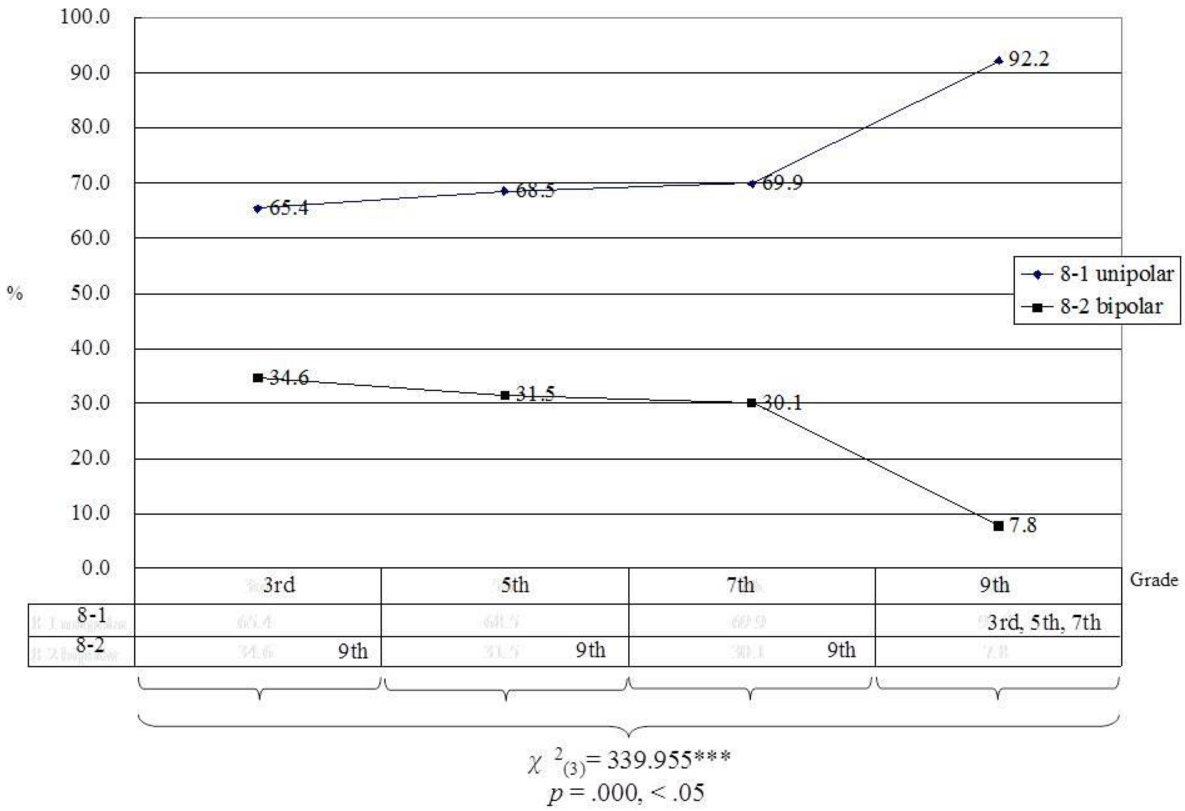


Figure 5. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 8, "polarity"

unipolar is more likely to be confused with initial concepts of the unipolar model. Thus, the proportion of grade 3 students with 8-1 is higher than expected. Therefore, the CET in electric circuits explains the inconsistency between the curriculum and the empirical data.

The proportion of *bipolar* C-statuses (8-2) was highest in grade 3, and the trend in **Figure 5** shows that the proportion could be higher than 34.6% before grade 3. It is likely to be the most frequent polarity C-status. In the CET in electric circuits prediction, the *bipolar* C-status (8-2) is the first C-character in the initial conceptual evolution, and it is a concept that students tend to have in the conceptual evolution of electricity. This hypothesis could be verified if children below grade 3 complete the electricity diagnostic test. However, this study did not include these children. Overall, student evolutionary pathway mental models in electric circuits do not conflict with the interpretation of the polarity C-character.

C-character 10—Current Direction

The current direction C-statuses are *unipolar direction* (10-0), *bidirectional current* (10-1), *scientific unidirectional current* (10-2), *crossing current* (10-3), and *from bulb to battery* (10-4). **Figure 6** shows that each C-status was distributed significantly differently in each grade ($\chi^2_{(3)}$

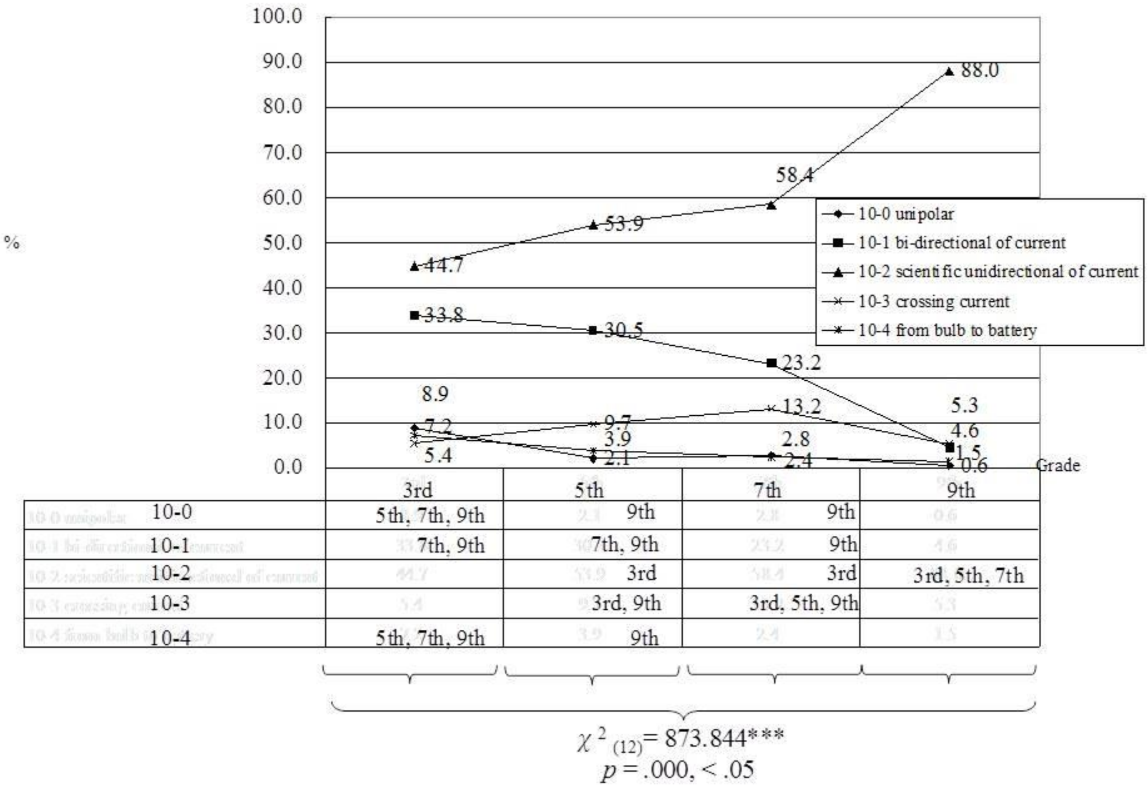


Figure 6. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 10, "direction of current"

= 873.844, p = .000). The post hoc comparison shows that the *bidirectional current*, *unipolar*, and *from bulb to battery* trends declined by grade. *Bidirectional current* decreased from grades 5 to 7 and grades 7 to 9. Unipolar and from bulb to battery decreased from grades 3 to 5 and grades 7 to 9. *Scientific unidirectional current* increased with grade, mainly from grades 3 to 5 and grades 7 to 9. This is consistent with circuit teaching in grade 4 and electricity concepts in grade 9. *Crossing current* increased from 5.4% to 13.2% from grades 3 to 7 and then declined to 5.3% in grade 9. The reason for this may relate to the teaching of electric motors and alternating current in grade 6 (**Table 1**). Our first validation also showed this phenomena (Lin & Chiu, 2009a).

Comparing the proportion of C-characters in each grade, the highest in grade 3 is 10-2 *scientific unidirectional current* (44.7%), followed by 10-1 *bidirectional current* (33.8%). According to this trend, the proportion of *bidirectional current* should be higher before grade 3. Thus, 10-1 should be the first C-status developed before grade 3, and 10-2 should be the second. The CET in electric circuits predicts that the first C-character on current direction is *bidirectional current* (10-1) and that *scientific unidirectional current* (10-2) is between Nodes 16 and 15. **Figure 4** shows that *crossing current* (10-3) appears on the CET in electric circuits branch after *scientific unidirectional current* (10-2). This study predicts that after the main C-status (*scientific*

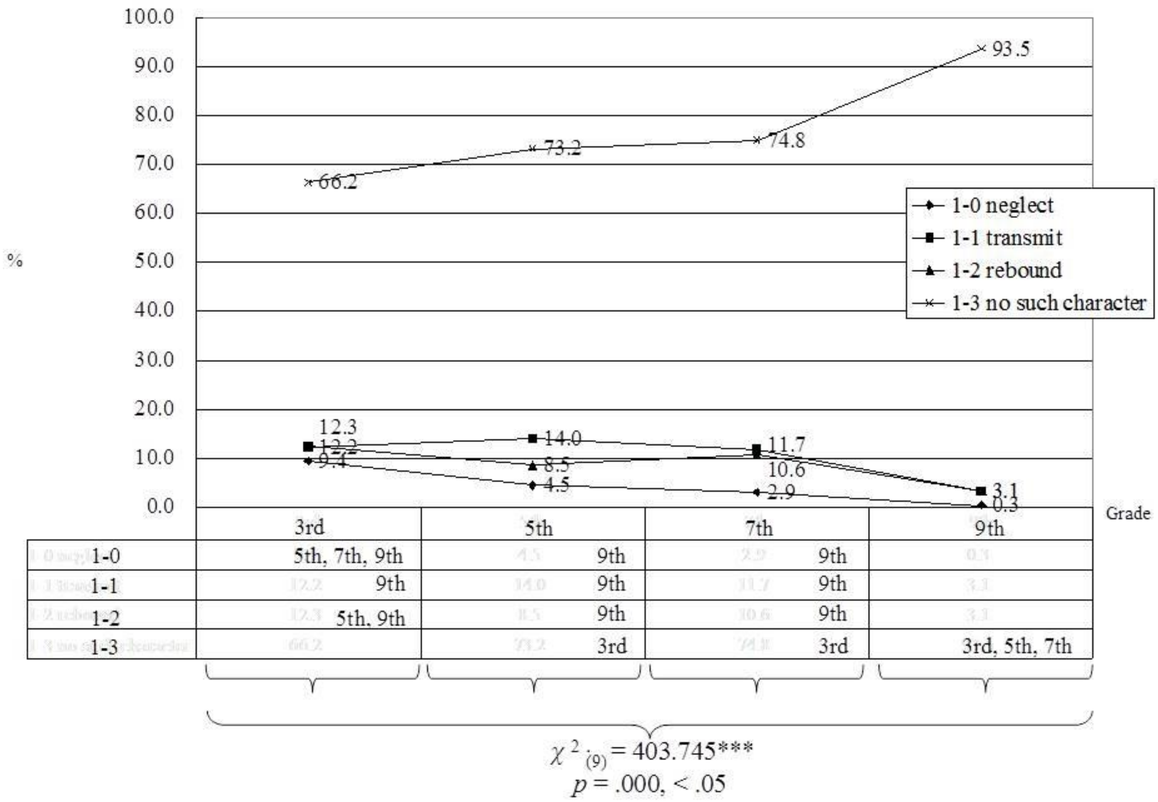


Figure 7. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 1, "current between two bulbs"

unidirectional current), the proportion of students with *crossing current* will increase. However, this is not on the main pathway; therefore, it may decrease after formal instruction. **Figure 6** shows that the percentage of *scientific unidirectional current* increases after grade 3 and is above 50% by grade 5, becoming the top C-status. The *crossing current* (10-3) C-status increased from 5.4% in grade 3 to 13.2% in grade 7 and decreased to 5.3% in grade 9. Therefore, the CET in electric circuits prediction and empirical data are consistent for C-character 10.

C-character 1—Current Between Two Bulbs

This C-character is a specific character which belongs to the three sub-models of B. bipolar model in Chiu and Lin's (2005) study. In all three submodels, current flows from the two poles of a battery to two bulbs and the bulbs shine because it absorbs current or because two currents bump in the bulbs. The differences between the submodels are student ideas on current distribution between two bulbs in a series connection. These differences are reflected by four C-statuses: *neglect* (1-0), *transmit* (1-1), *rebound* (1-2), and *no such character* (1-3). In **Figure 7**, the proportion of C-statuses in each grade was significantly different ($\chi^2_{(9)} = 403.745$, $p = .000$). As grade increased, the proportion of *no such character* increased (grade 3 to 9—66.2% to 93.5%). After a post hoc comparison, this increase was mainly from grades 3 to 5 and grades

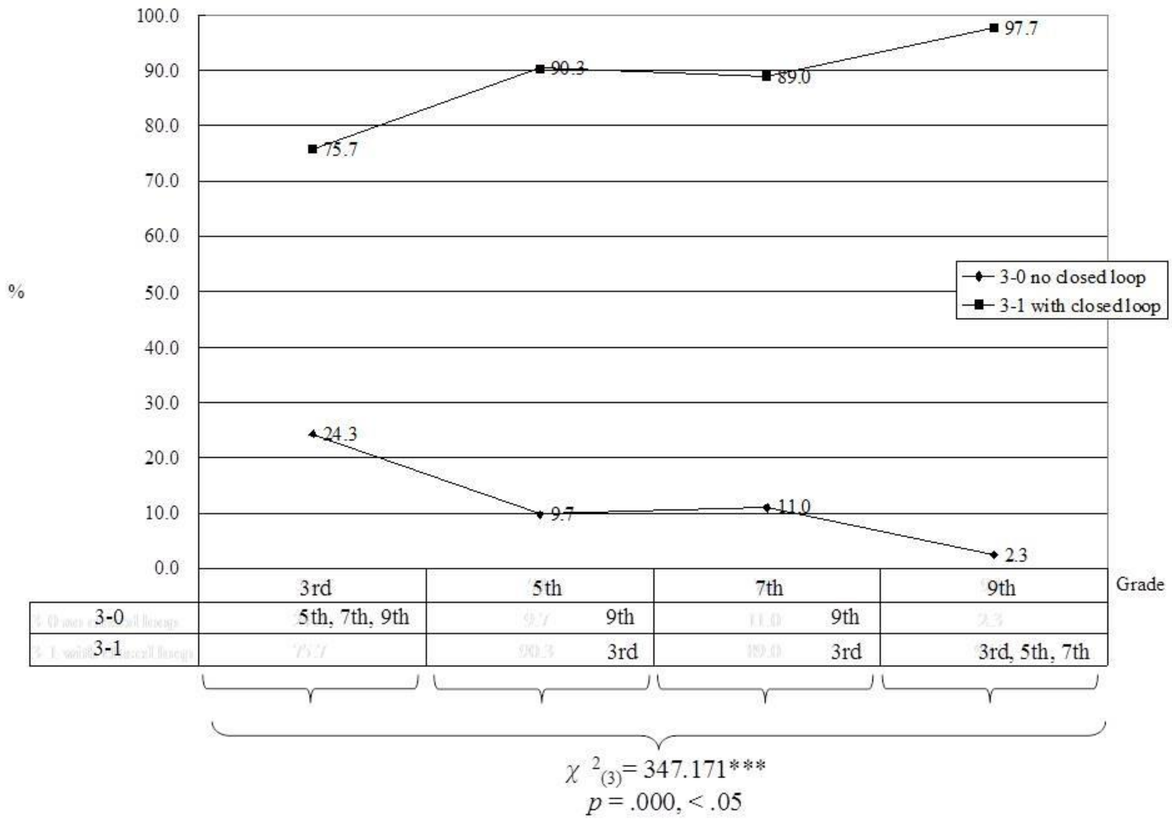


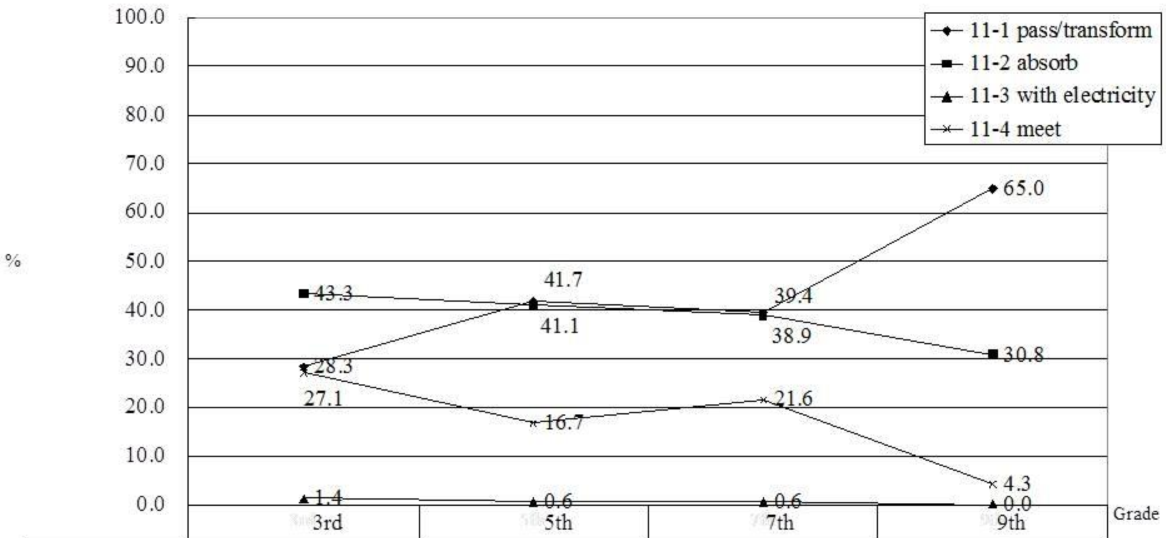
Figure 8. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 3, “closed loop”

7 to 9. The first increase corresponds to teaching the circuit in grade 4, and the second increase corresponds with teaching current, voltage, and resistance in grade 9 (**Table 1**). In grade 3, the proportion of *rebound*, *transmit*, and *neglect* was 12.3%, 12.2%, and 9.4%, respectively. *Rebound* and *transmit* were higher in grade 3. Comparing the three statuses shows that the proportion of *neglect* and *rebound* decreased significantly from grades 3 to 5 and grades 7 to 9, but *transmit* only decreased significantly from grades 7 to 9.

In the CET in electric circuits (**Figure 4**), *neglect* (1-0), *rebound* (1-2), and *transmit* (1-1) are not on the main evolutionary pathway. Each of these proportions is much lower than 50% in the empirical investigation, which corresponds with the prediction. The scientific concept, *no such character* (1-3), is more than 50% before grade 3, which also corresponds with the root of the evolutionary tree.

C-character 3—Closed Loop

The *closed loop C-statuses* are “*with closed loop* (3-1) and *no closed loop* (3-0). In **Figure 8**, the proportion of grade 3 students with *with closed loop* C-status was 75.7%. This increased with grade. In grade 9, nearly 100% of the students had this C-status. The chi-square test for



	3rd	5th	7th	9th
11-1		3rd	3rd	3rd, 5th, 7th
11-2	9th	9th	9th	
11-3	9th			
11-4	5th, 7th, 9th	9th	5th, 9th	

$\chi^2_{(9)} = 523.069^{***}$
$p = .000, < .05$

Figure 9. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 11, "role of a bulb"

homogeneity showed that the proportion of C-statuses in each grade was significantly different ($\chi^2_{(3)} = 347.171$, $p = .000$). Two significant increases occurred from grades 3 to 5 and grades 7 to 9, with no significant difference from grades 5 to 7. This may be caused by learning the circuit in grade 4 and teaching the main electricity concepts in grade 9.

In the CET in electric circuits (**Figure 4**), the *with closed loop* (3-1) C-status, which is at the beginning of the evolutionary pathway, appears between Nodes 18 and 17. The status of the C-character does not change thereafter. The proportional distribution (**Figure 8**) shows that the proportion of grade 3 students with this C-character is 75.7%; therefore, the prediction and investigation results correspond.

C-character 11—Role of a Bulb

The C-statuses for *role of a bulb* are *pass/transform* (11-1), *absorb* (11-2), *with electricity* (11-3), and *meet* (11-4). The chi-square test for homogeneity shows that the proportion of C-statuses in each grade was significantly different ($\chi^2_{(9)} = 523.069$, $p = .000$; **Figure 9**). The *meet* C-status indicates that current meets or collides in the bulb, making it shine. The proportion of this C-status in grade 3 was 27.1%. As grade increased, the proportion of this C-status decreased, until it reached 4.3% in grade 9. Although this C-status did not exceed 50%, an extension of the trend indicates that it was likely to exceed 50% before grade 3. Therefore, it may be the first C-status developed before grade 3. C-status *absorb* means that the bulb absorbs current from the battery and then shines. In grade 3, the proportion of students with this C-status was the highest (43.3%). After grade 3, the proportion decreased slightly. By grade 9, it decreased significantly to 30.8% and was ranked second. Therefore, it is probably the second C-character developed. In grade 9, the proportion of *pass/transmit* exceeded 50% (65%) and was ranked first. This C-status indicates that the bulb shines because current transforms electric energy into heat and light in the tungsten wire of the bulb. Only 28.3% of third graders had this C-status. It increased significantly from 39.4% to 65% between grades 7 and 9. It is probably the third C-status developed. This may be because Ohm's law is taught in grade 9 (**Table 1**). The *with electricity* C-status indicates that the bulb discharges current itself, and when current flows through the battery, this increases. Therefore, as current flows to the next bulb in a series connection, the bulb becomes brighter. This C-status clearly conflicts with the observed phenomenon; therefore, the percentage of this C-status was extremely low (0% to 1.4%). The teaching of route concepts in grade 4 may help students realize that current does not meet in the bulb and make it shine. Therefore, in **Figure 9**, the proportional distribution, chi-square test for homogeneity, and post hoc comparison show that the C-status *meet* decreased. It also decreased from grades 7 to 9 because electricity concepts are taught in the beginning of grade 9 (**Table 1**). Because of the two decreases, there was a significant increase in the proportion of C-status *pass/transmit*.

In the CET in electric circuits (**Figure 4**), *meet* is the first C-status of the C-character *role of a bulb* (11-4). It appears between Nodes 18 and 17, which is in the same internode as the C-status *with closed loop* (3-1). This indicates that the percentages of the two C-statuses should be similar and that students should have them at an earlier stage. Although **Figure 6** shows the percentages of grade 3 students having w*ith closed loop* (3-1) is 75.7%, and *meet* (11-4) only accounts for 27.1%. The figures vary considerably. The prediction of the CET in electric circuits shows both of the two C-statuses could appear before grade 3. Accordingly, the predication and the empirical data is still consistent. Furthermore, In the CET in electric circuits (**Figure 4**), the second C-status of the C-character is *absorb* (11-2). **Figure 9** shows that the proportion of this C-status was similar from grades 3 to 7, and in grade 3 it was ranked first at nearly 50%. Therefore, this C-status probably develops from grades 3 to 7. It is the second C-status developed, which corresponds with the evolutionary pathway prediction. In the evolutionary pathway prediction, the third C-status is *pass/ transform* (11-1). **Figure 9** indeed shows that this C-status (11-1) was ranked first in grade 9. Therefore, the order of the three C-statuses corresponds with the evolutionary pathway prediction. The *with electricity* C-status (11-3) proportion remains low and does not appear on the main evolutionary pathway.

C-character 12—Current Conservation

Students often understand that electricity is matter; therefore, they divide the electric current between two bulbs to determine their brightness. The C-statuses for this C-character

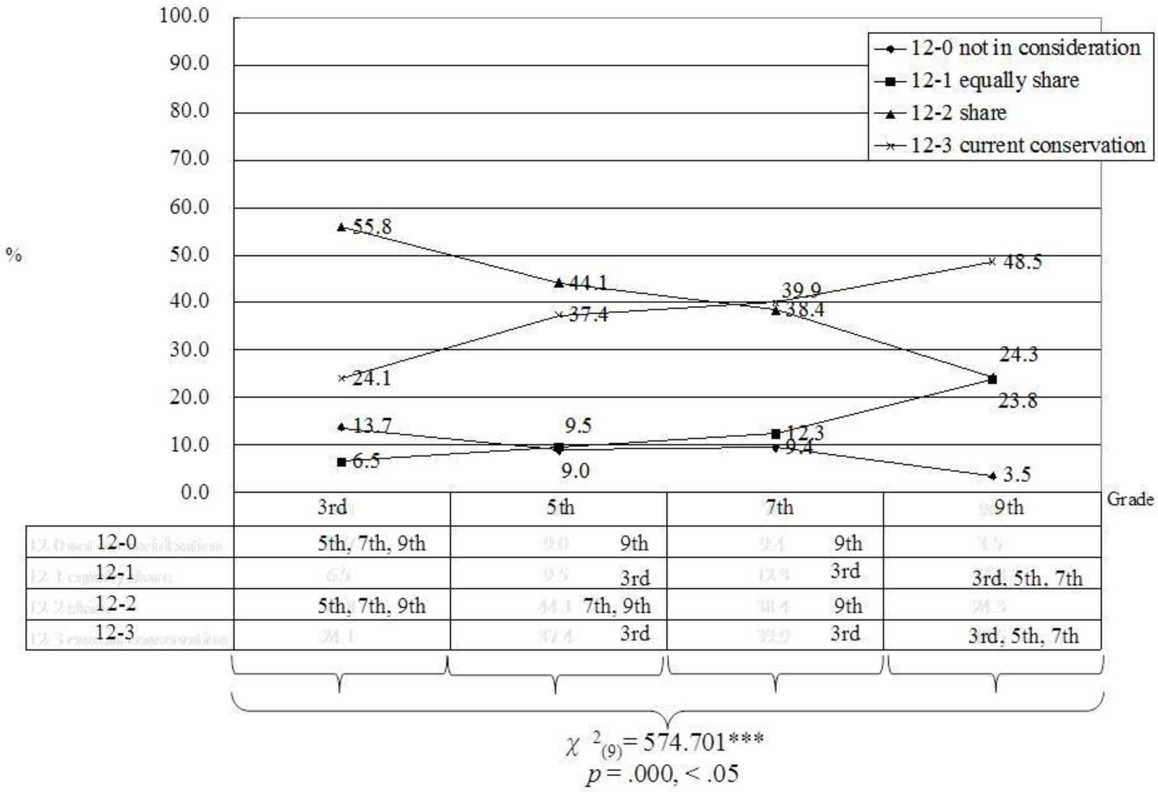


Figure 10. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 12, "current conservation"

are *share equally* (12-1), *share* (12-2), *current conservation* (12-3), and *not considered* (12-0). Of them, the first three focus on the different division of electricity. *Share equally* means that the two bulbs receive equal current and are the same brightness. The second C-status, *share*, means that the bulb that encounters electric current first receives more electricity and is brighter. *Current conservation* is the scientific concept. It means that students no longer attempt to distribute electricity, but tend to use electric energy transformation to explain bulb brightness in a series connection. The last C-status, *not considered*, is a characteristic of the bipolar model. Because current originates from the two poles of a battery and one electric wire serves one bulb, there is no current distribution problem. The proportions of these C-statuses differ according to grade, and the chi-square test for homogeneity shows that these differences were significant ($\chi^2_{(9)}$ = 574.701, p = .000; **Figure 10**).

The highest C-status (with over 50%) in grade 3 was *share* (12-2). It was the first C-status developed. The proportion of this C-status decreased by grade. By contrast, the proportion of *share equally* (12-1) and *current conservation* (12-3) increased by grade. *Current conservation* almost reached 50% (48.5%) and was the second C-status developed in grade 9.

From a curricular perspective, *share* (12-2) was a major alternative conception that decreased significantly three times. The first decrease was between grades 3 and 5. This may be because of circuit experiments in grade 4 when students observe that two bulbs in a series connection are equally bright. The second decrease between grades 5 and 7 may have been caused by energy transfer lessons in grade 6. The last decrease was between grades 7 and 9. Teaching Ohm's law in grade 9 promotes student understanding of circuits and related electric energy concepts. Therefore, it helps students overcome their alternative current decay conception.

In the CET in electric circuits (**Figure 4**), *share* (12-2) is the first C-status developed. The data show that this C-status exceeds 50% in grade 3. Therefore, it is reasonable that share is the first C-status developed. The second C-status developed, *share equally* (12-1), was between Nodes 14 and 13 in the middle of the evolutionary tree. Therefore, it was expected to be the highest proportion in grades 5 or 7. However, the data in **Figure 10** show that C-status 12-1 increased substantially from grade 7 to 9, which is later than the CET in electric circuits predication, and its proportion was less than 50%. The prediction was not consistent with the actual data. *Current conservation* (12-3) appeared between Nodes 13 and 12 at the end of the evolutionary tree. **Figure 10** shows that this C-status increased twice. It had the highest proportion and increased by almost 50% between grades 7 and 9. This was consistent with the evolutionary tree prediction. Therefore, except for the *share equally* prediction, the predictions were consistent with the empirical data.

C-character 2—Route

This C-character had two C-statuses: *with route* (2-1) and *no route* (2-0). The proportion of these two C-statuses differed by grade, and the chi-square test for homogeneity showed a significant difference ($\chi^2_{(3)}$ = 518.611, p = .000). In **Figure 11**, the proportion of third graders with *with route* was 53.9%. By grade 9, 90.4% of students had this C-status. The post hoc comparsion and C-status trend showed two obvious increases: one from grades 3 to 5 and the other from grades 7 to 9. This corresponds with teaching the circuit in grades 4 and 9 (**Table 1**).

In the CET in electric circuits (**Figure 4**), the *with route* C-status (2-1) (in the middle of the evolutionary pathway) appeared between Nodes 16 and 15 and did not change thereafter. This was similar to the *with closed loop* C-status (3-1), but the C-status (3-1) was in the preceding part of the evolutionary pathway and was held by students at an earlier stage. Therefore, the proportion of grade 3 students with this C-status was ranked first and accounts for 75.7% (**Figure 8**), whereas the proportion of grade 3 students with C-status 2-1 was 53.9% (which was also ranked first). By grade 5 this increased to 78.5%, but its evolution lagged behind the *with*

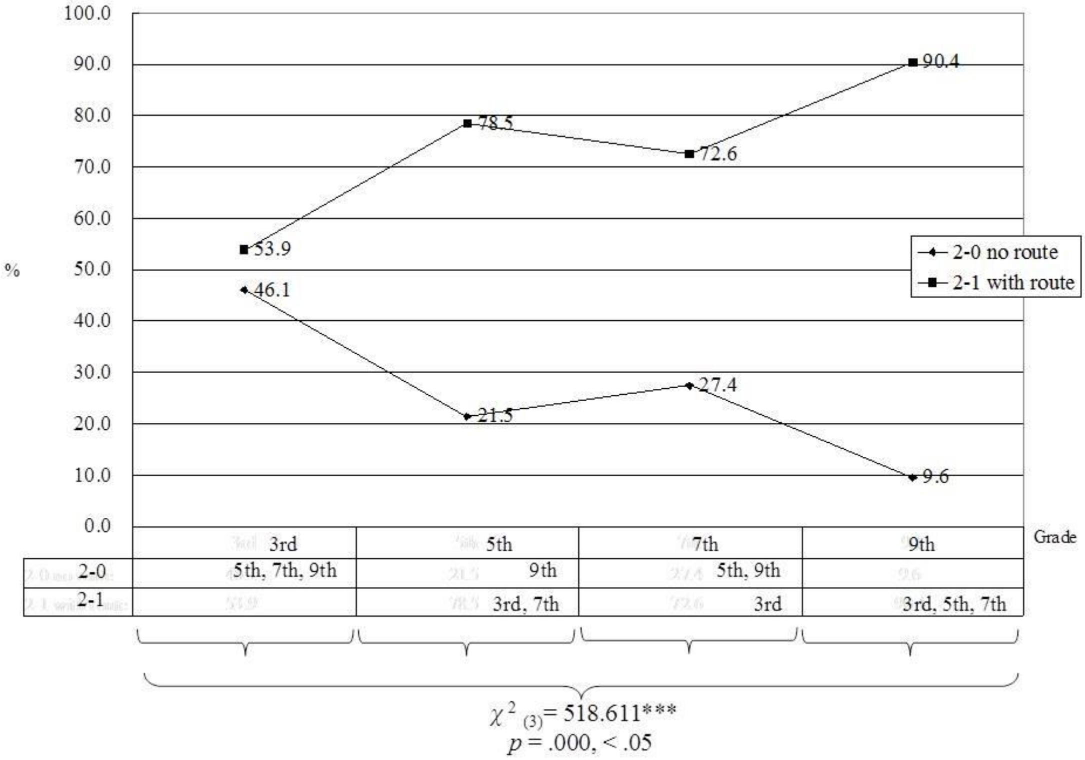


Figure 11. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 2, "route"

closed loop C-character by approximately 20%. This confirmed the prediction that this C-status occurred after the *with closed loop* C-status.

C-character 6—Systemwide

The systemwide C-statuses were *with systemwide* (6-1) and *without systemwide* (6-0). The proportions of these C-statuses differed by grade, and the chi-square test for homogeneity showed that these differences were significant ($\chi^2_{(3)}$ = 701.424, p = .000). In **Figure 12**, the proportion of *without systemwide* was ranked first, accounting for 75.1% in grade 3. In grade 5, the first significant decrease accounted for 59.6%. The second significant decrease was from grades 7 to 9 from 54.3% to 26.9%. *With systemwide* showed a reverse trend. Its proportion increased significantly twice, reaching 73.1% by grade 9. It almost exceeded 50% in grade 7 (45.7%). In grade 9, it was substantially more than 50%. Generally, younger students used the *without systemwide* C-status. The teaching of the circuit in grade 4 and in the first semester of grade 9 helped students view the circuit as a system. This supports the increase of C-status 6-1 at these two stages.

In the CET in electric circuits (**Figure 4**), the *systemwide* C-status (6-1) appeared between Nodes 14 and 13 and was in the middle of the evolutionary pathway. This C-status did not change after this position. **Figure 12** shows that the proportion of this C-status

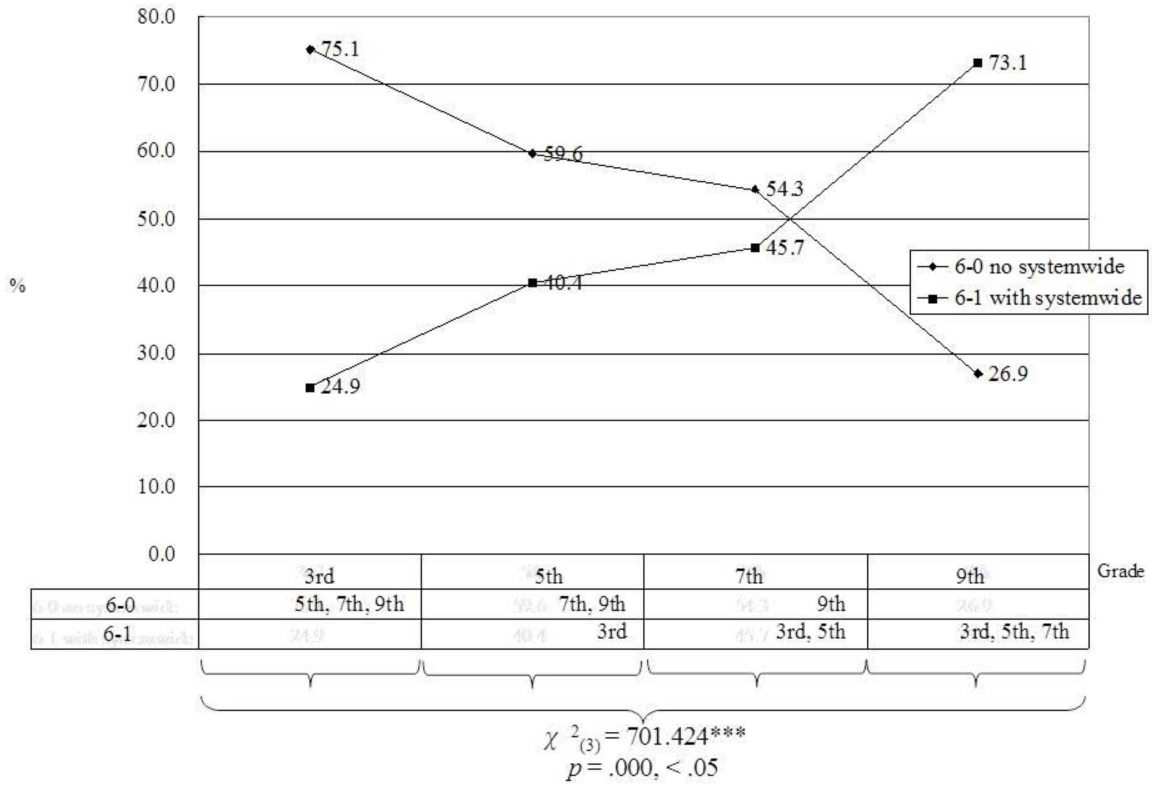


Figure 12. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 6, "systemwide"

increased significantly after grade 7 (from 45.7% to 73.1%). It is an endstage C-status, and corresponds with the end (later stages) of the evolutionary pathway.

C-character 5—Revised Sequential Inference Model

The revised sequential inference model C-statuses were the *sequential inference model* (5-1) and the *revised sequential inference model* (5-0). The proportions of these two C-statuses differed by grade, and the chi-square test for homogeneity showed that these differences were significant ($\chi^2_{(3)}$ = 492.333, p = .000). **Figure 13** shows that younger students mainly used the *sequential inference model*. This could be the first C-status developed because its percentage exceeded 50% (68.6%) in grade 3. Thereafter, the C-status decreased twice: once from grades 3 to 5 (68.6% to 52.9%) and once from grades 7 to 9 (48.6% to 27.7%). The *revised sequential inference model* increased significantly from grades 3 to 5 and from grades 7 to 9. In Grade 7, the proportion C-status *revised sequential inference model* was ranked first and accounted for over 50%. Therefore, it was the second C-status developed. Teaching circuit and electricity in grade 4 and grade 9, respectively, may have helped students learn this concept. Therefore, the curriculum and the two significant C-status increases were consistent.

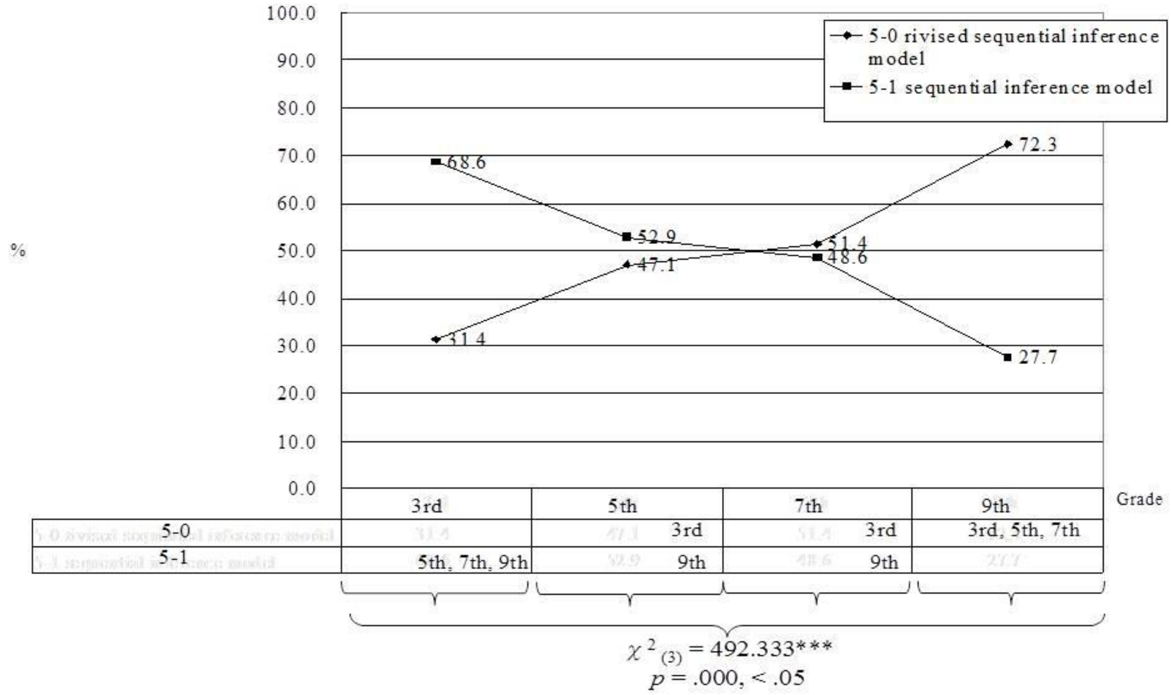


Figure 13. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 5, "revised sequential inference model"

In the CET in electric circuits (**Figure 4**), the C-status *revised sequential inference model* (5-0) appeared between Nodes 13 and 12. It was at the end of the evolutionary pathway and did not change thereafter. **Figure 13** shows that the C-status reached 50% by grade 7 and then increased substantially (51.4% to 72.3%). It is a C-status students have at an end stage, which corresponds with its position in the evolutionary pathway.

C-character 7—Revised Source-Consumer Model

The C-character revised source-consumer model consists of the *revised source-consumer model* (7-0) and *source-consumer model* (7-1). **Figure 14** shows that younger students mainly had the C-status *source-consumer model*. The proportion of grade 3 students with this C-status was 72.4%. This decreased to 62.8% in grade 5 and 57% in grade 7. However, the *source-consumer model* was ranked first before grade 7. It decreased substantially to 21.2% in grade 9 when the *source-consumer model* became the first C-status (78.8%). Connecting this result with the curriculum, teaching the circuit in grade 4 and electricity in grade 6 introduced forms of energy and energy conversion. Because the curriculum did not only focus on electric energy, the *revised source-consumer model* increased from grades 3 to 5 (27.6% to 37.2%) and from grades 5 to 7 (37.2% to 43%). Teaching electricity concepts such as current, voltage, and resistance in the first semester of grade 9 helped students understand electricity better, which may be why students used the C-status *revised source-consumer model*. The curriculum and C-status proportions correspond well with each other.

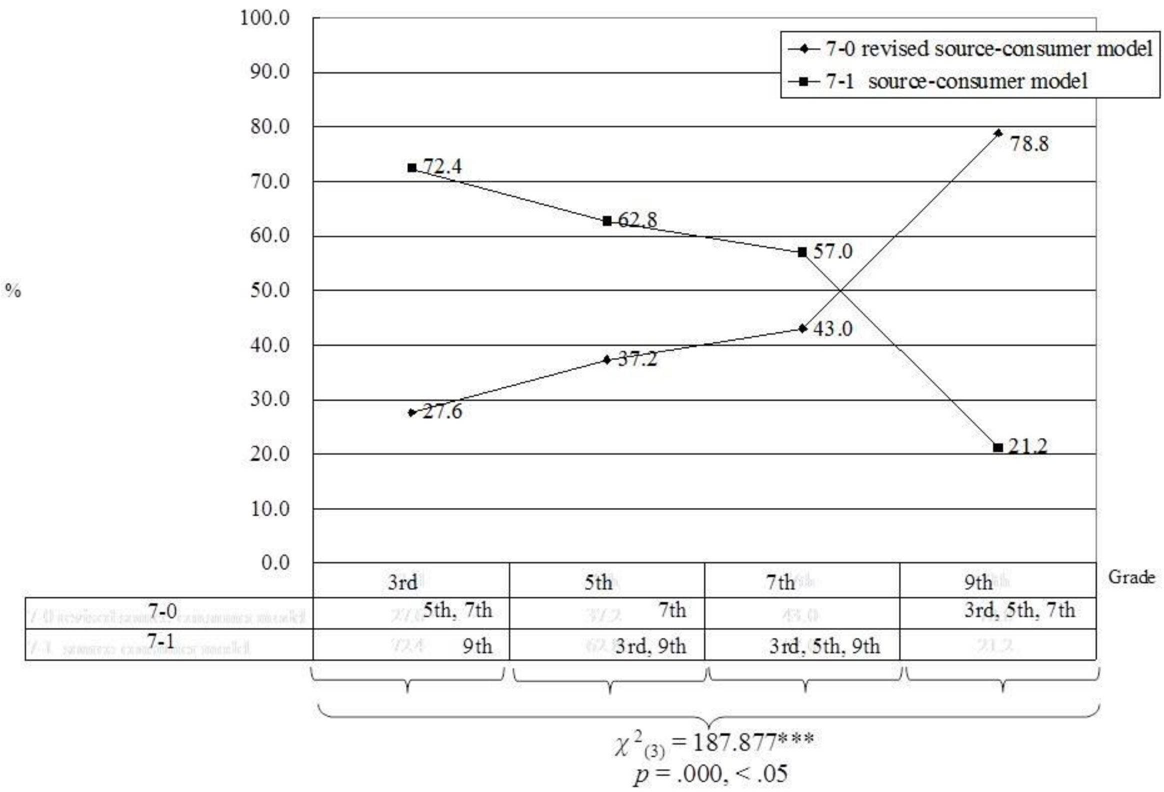


Figure 14. Proportional distribution, chi-square test for homogeneity and post hoc comparison of C-character 7, "revised source-consumer model"

In the CET in electric circuits (**Figure 4**), the C-status *revised source-consumer model* appears between Node 12 and mental model D3. It is the last C-status and appears at the end of the evolutionary pathway. **Figure 14** shows that the proportion of this C-status increased slightly from grades 3 to 7, but remained below 50%. By grade 9 it increased substantially (43%-78.8%). This trend confirms the CET in electric circuits prediction.

The empirical data were integrated with the CET in electric circuits to create an analysis graph of student C-character mental model evolutionary processes of electric circuits (**Figure 14**). The graph enables the hypothetical CET in electric circuits prediction to be compared to the empirical investigation and be validated.

CONCLUSIONS AND IMPLICATIONS

Summing up the results in this study, two conclusions are below:

CET in Electric Circuits Predictions Correspond Approximately with the Proportional Distribution Investigation

The first conclusion is from the combination of research questions one and two. This study selected 10 C-characters from a diagnostic test and Lin's CET in electric circuits (Lin, 2006; Lin & Chiu, 2006). The timing of the main C-status was considered according to the first ranked C-character C-statuses and whether the C-status proportion exceeded 50%. A comparison of the cross-grade investigation data and the CET in electric circuits showed that the CET in electric circuits interpreted most changes in student C-statuses, conceptual increases, and conceptual revisions—that is, the whole evolutionary process. However, a difference between the empirical investigation and the CET in electric circuits prediction still exists. Even when we revised the item of C-character 12, the distribution of current conservation (12-3) was too low (6.5% to 23.8%) in the empirical investigation. This is also inconsistent with the literature (e.g., Chiu & Lin, 2005; Osborne & Freyberg, 1985; Shen et al., 2007; Shipstone, 1984, 1985).

Curriculum Guidelines Generally Explain the Learning Process of Student Concepts of Circuits

The second conclusion answers the third research question. If the CET in electric circuits prediction is totally accepted, what is the relationship between the curriculum and the hypothetical evolutionary pathways of students' mental models in electric circuits? In **Figure 4**, the Taiwanese curriculum guidelines (**Table 1**) generally parallel the learning process of student concepts of circuits. The learning progress of the *revised sequential inference model* (5-0), *role of a bulb (pass/transmit)* (11-1), and *revised source-consumer model* (7-0) is ***ahead*** of the evolutionary pathway prediction (the proportion is much higher than 50% or the concept developed at an earlier stage). *Current conservation* (12-3) developed ***a little later*** than predicted. This may be because the curriculum does not emphasize the alternative conception of bulb brightness, where students see current as a substance that can be allocated. Therefore, future curricula should refer to the incorrect ontological perspective, which regards current as a substance. The CET in electric circuits indicates that understanding of *route* (2-1) and *scientific unidirectional current* (10-2) are accompanied by the alternative role of a bulb conception, *absorb* (11-2). Heller and Finley (1992) and Shipstone (1984) also reminded teachers to notice this point. The percentages of these three C-statuses in grade 3 are similar to those found in the Lin and Chiu (2009a) study. Thus, future curricular design should focus more on this.

Some researchers have stated that life experience and teaching tracking current flow lead to the sequential inference model (Arnold & Millar, 1988; Cohen, 1984; Duit, 1984; Tiberghien, 1983). Other researchers have claimed that students think that “voltage is current” because they are taught current too early (Cohen, 1984; Von Rhoneck, 1984). However, the CET in electric circuits shows that, although life experiences could influence the sequential inference model, it may be deeply rooted in students’ alternative conceptions before current direction is taught. Student focus on current may confirm the evolutionary process of student concepts; therefore, they may easily ignore voltage. Comparing the CET in electric circuits prediction to the C-character data shows that most students use the revised sequential inference model and revised source-consumer model by grade 9 or above. They also use electric field concepts instead of current allocation to interpret electricity. Thses imply not only approprite curriculum but also students' cognitive development could assist students in better understanding of these difficult C-characters.

Based on the conclusions, three implications are emerged.

Whole Picture of the Evolution of Student Mental Models in Electric Circuits Reveals

Researchers can use trandistional cross-age or cross-grade studies to examine the development of *single* concepts. However, the cladistics approach in conceptual evolution constructs an evolutionary pathway of student mental models in electric circuits and creates an explicit representation to interpret the *overall picture* of the evolution of these models in a systematic manner.

The thick line in **Figure 4** shows the electric circuit mental models for more than half of the students. Students before grade 3 mostly use the *bipolar* concept (8-2). They think that current originates from *bipolar* of a battery (10-1) and that these currents *meet* in the bulb (11-4), making it shine. The bulb, wire, and battery must be connected in a *closed loop* (3-1) to make the bulb shine. C-character timing is unclear between grades 3 and 5, and students tend to use the concept that current is *shared* between bulbs (12-2) instead of the concept of current conservation. When most students begin to use the concept of *route* (2-1), they also use the concept of *scientific unidirectional current* (10-2). They do not think that the bulb shines because the current originates from the two battery poles, meets, and makes the bulb shine. Scientific unidirectional current means that students think the bulb *absorbs* current and shines (11-2).

The C-status that students revise in grade 5 is the *unipolar* battery (8-1). From grades 7 to 9, students have a better *systemwide* (6-1) understanding, and their ideas on current distribution change from *share* (12-2) to *share equally* (12-1). In grade 9, students gradually *overcome the sequential inference model* (5-0) and understand that *current is constant*, although it is *incorrect* (9-1), that electric energy *transforms* into light and heat to make a bulb shine (11-1), and that *current is conserved* (12-3). Later, students determine that there is voltage in a battery and they *no longer use the source-consumer model* (7-0). Therefore, they can understand and predict *current strength correctly* (9-2). At this point, more than half of the students use scientific models.

To understand the evolutionary pathways of students' mental models does not mean the curriculum designer *must follow* these sequences to design the instruction. Due to the complication of the evolutionary pathways of students' mental models, it not only exists the increase of scientific concepts but also the increase or revision of alternative conceptions. The Lin suggests researchers clarify the possible relationship between the evolutionary pathways of students' mental models and the development of curriculum. Then, consider the interaction of concepts and alternative conceptions to design teaching strategies and sequences in order to give judicious guidance according to students' developmental pathways and prepare in advance to help students achieve conceptual change. The last section of this study shows the possible relationship between the evolutionary pathways of students' mental models in electric circuits and the curriculum. Suggestions for curriculum and teaching that take this analysis of graph as foundation are also provided.

Future Studies Should Extend CET Approach to Other Topics

With the application of cladistics in biology, the results in this study show high validation of the CET in electric circuits. Therefore, the results verify the feasibility of applying this approach for students' mental model evolution. As for the dissimilarity in the cross-grade investigation of the study, it is recommended that future studies validate the findings. This innovative approach has been verified twice using electric circuit models. Because this approach can be used to develop experiments and collect evidence of different aspects, it is a more scientific approach than previous methods, irrespective of whether it supports or rejects a hypothesis. Future studies should extend this approach to other conceptual topics. Until now, the topics of *gas particles* (Chiu, Wu, Chung, & Li, 2013), *evolution theory* (Hsin & Chiu, 2010), *phase transitions* (Chiu & Wu, 2013) and *earth shape* (Lin & Wu, 2012) have been investigated and validated once via this approach. The research results were also almost consistent with other previous literature reviews. These studies not only re-verify the feasibility but also help us to understand the whole picture of students' conceptual evolution.

Adopting CET Approach to Assist Curriculum Design

The preliminary CET in electric circuits results can assist science educators to design the teaching-learning sequences, learning progression or model-based instruction based on different student mental models. Preliminary studies have shown that it is effective in improving student learning efficiency, diagnosing alternative conceptions (Lin & Chiu, 2009b), and student self-assessment attitudes (Lin & Chiu, 2009c). Future studies should design different teaching-learning sequences or learning progression using the evolutionary pathways of student mental models and use empirical methods to explore different conception sequences and teaching strategies in actual classes to clarify which teaching-learning sequences, learning progression or model-based instruction best improves student learning.

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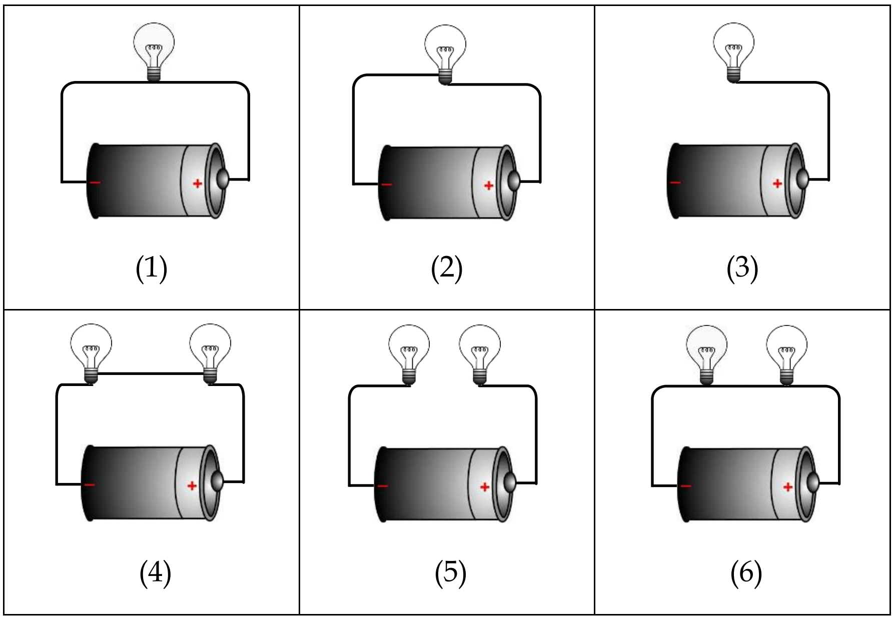
APPENDIX

Electricity Diagnostic Test

Grade:____ Class:_____ Number:___ Name: __________

Part I 1. Drawing

1. Connect the battery, the electric wire, and the bulb in the ways as illustrated in the following pictures. Which bulb(s) will shine? Please draw lines over the bulbs which can lighten up like: 



2. Of the six pictures above, which of them has/have an electric current that flows in the circuit? Please indicate the direction of the electric current flow in those pictures. (Please use ‘ → ’ to show the direction of each electric current flow; if necessary, you also can use ‘ 1 ’ , ‘ 2 ’ and so on to help you express the order of flow of the electric currents.)

Part II Compare the Current Intensity of Different Circuits

Compare the amperage at each of the positions in FIGURE 1 below. Which one is large? Choose an appropriate symbol to represent this relationship.

( ) 1. (1)A>B (2)A<B (3)A=B

( ) 2. (1)C>D (2)C<D (3)C=D

( ) 3. (1)E>F (2)E<F (3)E=F

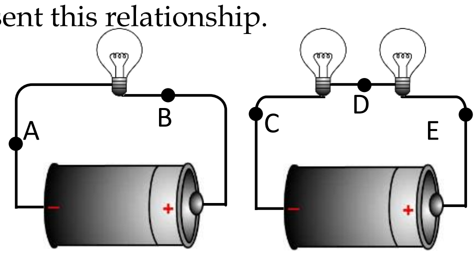


FIGURE 1

Part III Two-tier Diagnostic Items

1. The two bulbs in FIGURE 2 from the preceding question are of the same type. Which of the following descriptions about the brightness of the bulbs is the most reasonable?

First tier

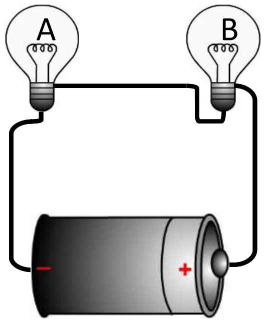


FIGURE 2

( ) A. A is brighter.
B. B is brighter.
C. A is as bright as B.
D. Both of these two bulbs cannot shine.

Second tier

( ) A1. Because the electric current flows from '—' and first passes through A ***which takes up most of the electric current***. Only a small part of the remaining electric current passes through B.

A2. Because there is ***electricity*** in A; the electric current flows from B, and then passes through A which takes most of the electric current. After that, the electric current goes back to the battery which ***resupplies*** electricity. Therefore, A becomes brighter.

B1. Because the electric current flows from '+' and first passes through B which takes up most of the electric current. Only a small part of the remaining electric current passes through A.

B2. Because there is electricity in B; the electric current flows from B, and then passes through A which takes most of the electric current. After that, the electric current goes back to the battery which resupplies electricity. Therefore, B becomes brighter.

C1. Because there are two streams of electric current flowing from the two poles meet each other between the two bulbs and are then bounced back to the bulbs resulting in a crash that lightens bulbs up.

C2. Because there are two streams of electric current flowing from the two poles; they passes through the first bulb which absorbs a small part of the electric current and then they flow to the next bulb. Besides, the electric current will flow back and forth between the two bulbs.

C3. Because the electric currents in the whole electric circuit are equal. Also, the bulbs will not consume any electric current.

C4. Because the electric current flows from the battery, and it has to be equally distributed to the two bulbs.

C5. Because the electric current flows from '+' pole to the '-' pole via the bulbs, and then will restart to flow from the '-' pole to the '+' pole via the bulbs. The electric current flows in these two ways by taking turns.

D1. Because the two electric wires which connect to the bulbs don't connect to battery directly. There is no electric current.

2. Which of the following descriptions about the light conditions of the two bulbs is the most reasonable if we cut the electric wire between the two bulbs as shown in FIGURE 3?

First tier

( ) A. A can shine, but B cannot.
B. B can shine, but A cannot.
C. Both of these tow bulbs can.
D. Neither A nor B cannot.

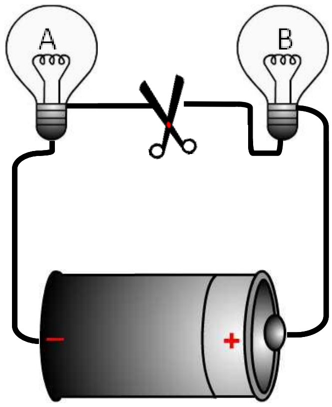


FIGURE 3

Second tier

( ) A1. Because the electric current can flow from the '−' pole to A; but it cannot continue to flow to B.
B1. Because the electric current can flow from the '+' pole to B; but it cannot continue to flow to A.
C1. Because the electric current can flow from the '−' pole to A and also can flow from the '+' pole to B, therefore both of the two bulbs will shine.
D1. Because the wire is cut off resulting in an open circuit, there is no electric current in the circuit.
D2. Because the electric current flows halfway through the circuit but cannot go further, therefore both of the two bulbs will not shine.
D3. Because the electric current from the '−' pole flows halfway through the circuit but cannot go further; the electric current from the '+' pole flows halfway through the circuit but cannot go further either. Therefore, both of the two bulbs will not shine.

3. There are two batteries with the same voltage (3V) but different sizes. That is, the power to push electric charges of these two batteries is 3 voltages and equal. Connect an A battery to a bulb (FIGURE 4) and connect an AAA battery to a bulb (FIGURE 5), which of the following descriptions about the brightness of bulbs is the most reasonable? The bulb which connects the A battery ……

First tier

( ) A. A is brighter.
B. The brightness is equal.

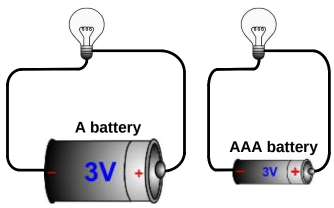


FIGURE 4 FIGURE 5

Second tier

( ) A1. The size of the A battery is bigger, and it contains more electric current, so the bulb which connects to A batter is brighter.

B1. The brightness of two bulbs is equal. Although ***the using time is extended*** for the bigger size of ***A*** battery which ***contains more electric current***.

B2. The size of the ***A*** battery is ***bigger***, and it ***contains more electric current***, but ***the thickness of wires is equal*** in two connections, they can ***convey equal current***, so the brightness of two bulbs is equal.

B3. Because ***the voltage of two batteries is equal*** (the power to push electric charges), so ***the electric current is equal*** in two connections and the brightness of two bulbs is equal.

4. To compare the current in points A and D, which of the following descriptions is the most reasonable?

First tier

( ) A. The current in point A is bigger than point D.

B. The current in point D is bigger than point A.

C. The current in point A is equal in point D.

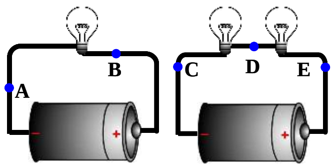


FIGURE 6 FIGURE 7

Second tier

( ) A1. Because point A is closer to the '—'pole which current flows, t***he wire that connects to the battery is shorter than the other one,*** the current in point A is bigger than point D.

A2. The current that flows to point A ***does not pass through a light bulb***, but the current that flows to point D ***has gone through a light bulb***, the current has been absorbed a small part by the light bulb, so the current in point A is bigger than point D.

A3. In FIGURE 6, the current of the battery is only given to one light bulb. In FIGURE 7, the current of the battery ***is equally shared by two light bulbs***, so the current in point A is bigger than point D.

A4. In the same battery, the same voltage, the more light bulbs are connected in a wire, the smaller current ***in this circuit system***. Therefore, the current in point A is bigger than point D.

B1. Because point D is closer to the ' + ' pole which current flows, t***he wire that connects to the battery is shorter than the other one,*** the current in point D is bigger than point A.

C1. The current that flows to point A ***passes through one light bulb***, the current that flows to point D also ***passes through one light bulb***. Both of the two currents are taken some parts by light bulbs, so the currents in two points are equal.

C2. The wire in two circuits is one. All light bulbs are connected by one wire. ***The battery supplies the same current to this wire***, so the current in point A is equal to in point D.

Part IV Multiple Choice Items

(   ) 1. This is a flashlight.  There are two batteries and one bulb inside the flashlight.

The bulb of a flashlight does not shine, but it shines again when the old batteries are replaced by new ones. Why the new batteries can make the bulb luminous?

(1) Because there is ***new electricity*** in the new batteries, the electric power is in more abundance.

(2) Because the new batteries ***store a lot of electricity inside***, they can ***release*** the electric current.

(3) Because there are some chemical substances in the new batteries which can undergo chemical changes ***transforming*** chemical energy into electrical energy.

(   ) 2. Why the bulbs will shine in <u>FIGURE 8</u>? This is because…

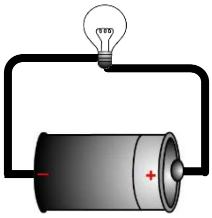


FIGURE 8

(1) The electric current can ***flow through*** the bulbs, so the bulbs will shine.

(2) The bulbs can ***absorb*** the electric current, so the bulbs will shine.

(3) Electric energy can be ***transformed*** into light energy in the bulbs, so the bulbs will shine.

(4) Two streams of electric currents ***crash into*** each other in the bulbs, so that the bulbs will shine.

(5) There is ***electricity in the bulbs***, and they ***absorb*** the electricity emitted from the battery. Therefore, the bulbs will shine.

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