



Abstract. Besides improving students' understanding of scientific concepts, chemistry teaching should also improve students' ability of applying concepts to solve problems. The research aims to explore the effects of modeling teaching on students' proficiency in solving galvanic cell problems. This research used a quasi-experimental design, and the independent variable of the research was the teaching method. Forty-five students in the experimental class received modeling teaching, and 48 students in the control class received lecture-style teaching. The dependent variable was the performance level of the student's ability to solve the problem of the galvanic cell, which was evaluated using the galvanic cell proficiency assessment tool. The research results show that the students in the experimental class were significantly more proficient in solving galvanic cell problems than those in the control class. The results of unstructured interviews assisted in illustrating the role of modeling teaching in improving the proficiency of students in solving galvanic cell problems, and students in the experimental class had positive views on modeling teaching.

Keywords: galvanic cells, modeling teaching, problem solving, proficiency level

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MODELING TEACHING IN STUDY OF GALVANIC CELLS: UPPER- SECONDARY SCHOOL CONTEXT

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Introduction

Unconventional skills such as complex problem solving are becoming increasingly important in this era (Wüstenberg et al., 2016). Problem solving not only plays an important role in STEM courses in middle schools and universities but also makes students more competitive when entering the workplace (Dunlap, 2005; Sevia et al., 2015). Science teaching should not only enable students to acquire a large amount of organized knowledge in a specific field but also, more importantly, equip students with the ability to solve problems in that field (Salta & Tzougraki, 2011; Yuriev et al., 2017). However, in the chemistry classroom, teachers still face the dilemma that students only remember factual knowledge and have a knowledge base, but they do not use the knowledge they have learned to solve problems (Bodner, 2004; Matijašević et al., 2016; Overton & Potter, 2011).

Modeling is one of the core skills of scientific inquiry (Maia & Justi, 2009). In many cases, the objects of scientific research are complex, abstract, and unobservable. Researchers often construct a simplified version that is not exactly equivalent to the prototype or form a conceptual model that abstracts some features, properties and laws of the prototype. Students can also benefit from modeling. Implementing modeling teaching gives students the opportunity to use their existing knowledge to conduct "thinking experiments" and have an in-depth understanding of the behavior of complex systems (Jackson et al., 1994), thereby developing their own understanding of natural phenomena, rather than merely memorize facts and definitions (Harrison & Treagust, 2000; Hestenes, 1995; Jong et al., 2005; Maia & Justi, 2009).

In the past, many researchers have confirmed the positive effect of modeling teaching on students' knowledge development and understanding of abstract concepts (Hestenes, 1995; Jong et al., 2005; Park et al., 2017). However, there is a lack of relevant research on the impact of modeling teaching on problem solving. No empirical research has tested the impact of modeling teaching on students' problem-solving abilities and the aspects of modeling teaching that are beneficial.

Model and Modeling

The simple term “model” contains many meanings (Miller & Kastens, 2018), and Gilbert et al.’s classification of a model according to its ontology can help us understand the meaning of models (Gilbert et al., 2000). Mental models are cognitive representations of individuals. Mental models can be expressed in the public domain through action, speech, writing or other symbolic forms. After being tested by the community of professional scientists, these expression models are recognized by society and play a central role in the research and development process, eventually becoming consensus models. The consensus models used at the forefront of science are called scientific models, and the consensus models generated under specific historical backgrounds are called historical models. Mental models, expression models and consensus models play key roles in guiding and disseminating scientific and technological achievements (Gilbert, 2004; Koponen, 2007; Oh & Oh, 2011). After simplification or processing, they become curriculum models, mixed models and teaching models used by teachers in the classroom, which play an important role in science teaching and learning (Cheng & Brown, 2015; Clement, 1989; Clement, 2008; Coll et al., 2005; Miller & Kastens, 2018).

Modeling refers to the behavior of generating, evaluating, modifying, and using/applying models (Gunstone, 2015). As the main founder of science modeling education, Hestenes first proposed that problem solving is a modeling process (Hestenes, 1987). The modeling process includes four stages: model construction, model analysis, model validation and model deployment (Hestenes, 1995). Halloun divides the modeling process of solving paradigm problems (presented in textbooks) into five stages: model selection, construction, verification, analysis and deployment (Halloun, 1996). Later, researchers constructed the modeling process based on different perspectives (Clement, 1989; Liu & Chiu, 2010). Although there are different perspectives of the modeling process, there are some basic elements to researchers’ understanding of the modeling process: identifying elements, constructing models, modifying models, and evaluating models.

The process of students’ participation in modeling activities should be consistent with the modeling practices of scientists (Fretz et al., 2002; Hestenes, 1995; Miller & Kastens, 2018). Therefore, some researchers have constructed the process of modeling teaching based on the understanding of modeling elements, but they have not paid much attention to the forming process of students’ individual mental models (Brewer, 2008; Halloun, 1996; Wells et al., 1995). One of the purposes of modeling teaching is to develop teaching strategies to establish, critique and change our mental model of how the world works (Khan, 2007). The knowledge and experience of students and scientists are different. Just as the scientific inquiry process of scientists is difficult to reproduce in students, the modeling experience of scientists cannot be directly applied to students. Modeling teaching needs to be concerned with students’ mental representations constructed in their interactions with the world, phenomena and artifacts, that is, students’ mental models.

Justi and Gilbert developed a “model of modeling” framework from the perspective of students’ mental model construction (Justi & Gilbert, 2002). All modeling is undertaken for a purpose: selecting the source of the model, constructing it based on the phenomenon described, and forming a mental model from existing resources or experiences. When a mental model is generated, decisions are made about how to express it: materially, visually, verbally, or mathematically. Having produced a model, the next step is to explore its meaning through a thought experiment carried out in the mind. If it passes the thought experiment stage, it can move on to the empirical test phase, where models are evaluated and modified. Finally, the application scope and limitations of the model are considered in the process of model promotion.

Although the “model of modeling” framework describes the internal mental activities of students’ modeling, it does not explain how to promote the occurrence of such mental activities in students during teaching, resulting in a lack of operability when teachers apply it to teaching.

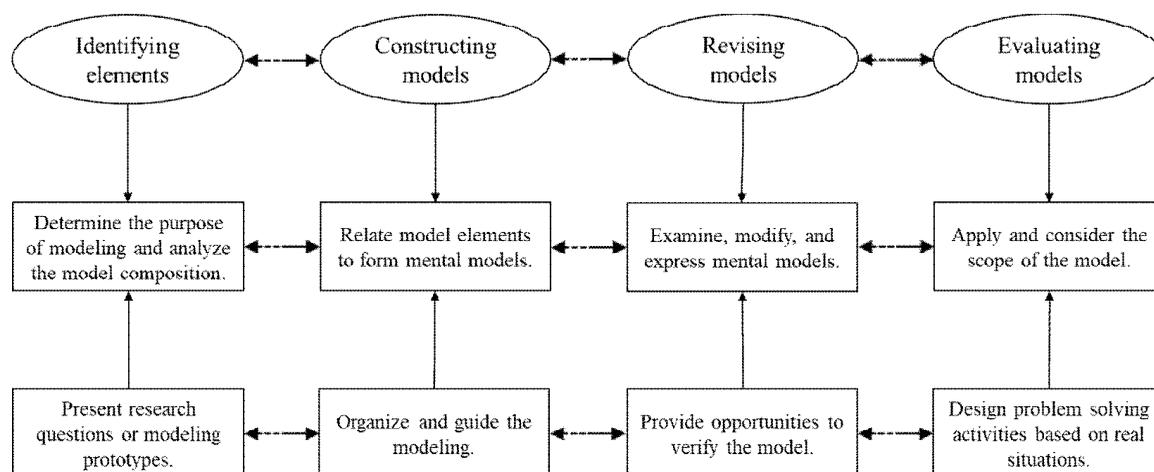
Model Teaching Program Structure

The teaching process includes two aspects of teaching and learning, which is to trigger, promote and maintain the students’ internal learning process through external events consciously arranged by the teacher (Gagné, 1985). Based on the basic elements of the modeling process, with the purpose of promoting the mental activities of students in modeling, the modeling teaching activities to be carried out by teachers were proposed, and the modeling teaching program structure integrating modeling elements, student activities and teacher activities was constructed (Figure 1). As shown in Figure 1, the modeling teaching program includes four main links, corre-



sponding to the four basic elements of the modeling process. The two-way arrows between the links indicate that students' modeling activities are not always unidirectional, and the construction of models is often a process of continuous revision and iteration. In each link, students' specific modeling activities and teachers' corresponding teaching activities are described below.

Figure 1
Model Teaching Program Structure



Identifying elements. The model includes the constituent elements and the connections between the elements. The first step in constructing a model is to extract the key elements of its structural features, functional features and behavioral characteristics. Students need to determine the purpose of modeling and the components of the model through analysis. On the one hand, teachers should present modeling prototypes or research problems to students, stimulate students' curiosity and make them think about the purpose of modeling. On the other hand, teachers should guide students to identify the key attributes/elements of the prototype and ignore the unimportant details, and use the discussion method to make the connotations, features and functions of each element clear to students, so that students' simple understanding of the elements can be transformed into scientific understanding.

Constructing models. Identifying elements is only the first step in constructing a conceptual model. At this step, students are exposed to many scattered concepts, but they form no meaningful connections between the elements. The central link of constructing a model is to establish the relation between elements. In this part, students will relate elements to form a mental model of a prototype. There are many ways to determine connections between elements. Teachers can ask students not only to provide descriptions with language but also to express their own ideas independently by drawing pictures. Teachers can understand the development of students' mental models through explicit language or graphics. When constructing a chemical model, teachers should encourage students to examine prototypes from macroscopic, microscopic and symbolic levels as much as possible. Students can gain a comprehensive and transferable understanding of scientific concepts through a deep understanding of the interactions between elements.

Revising models. Models contain many elements and their complex relationships, so the modeling process is not a linear process, but a cyclic and interactive process (Clement, 1989; Halloun, 1996; Hestenes, 2010; Liu & Chiu, 2010; Justi & Gilbert, 2002). Students need to constantly revise, examine, and express the formed mental model. Teachers need to provide students with opportunities to analyze and validate models so that students can demonstrate whether a model can describe or explain the problem and can assess the relevance of the explanation. Teachers can increase cognitive conflicts and high-level thinking activities among students by providing problems that require inquiry or critical thinking and that promote students' deep thinking about models.

Evaluating models. In order for the new model to be truly integrated into the students' knowledge system, students also need to master how to use and evaluate a new model, and apply the model to real, unfamiliar and complex situations. Students can consider the scope of application of the model in the process of applying the

model. On the one hand, students understand constructed models based on different situations; on the other hand, they use constructed models to describe, explain and predict new situations. By designing a variety of problem-solving activities based on real situations, teachers can provide students with opportunities to apply models, help them understand the meaning of the models, evaluate the effectiveness of the models and reflect on the construction and modification processes of the models.

Research Problem

In upper-secondary school chemistry courses, electrochemistry has always been considered one of the most difficult topics by students and teachers because of its abstractness and dynamics (De Jong & Treagust, 2002; Rogers et al., 2000). Although various studies have explored students' understanding of the topic of electrochemistry, they have found student have alternative conceptions and learning difficulties (Garnett & Treagust, 1992; Karsli, 2012; Rahayu et al., 2011; Schmidt et al., 2007), and different teaching strategies and teaching models have been applied to improve students' understanding of electrochemical abstract concepts (Doymus et al., 2010; Özkaya et al., 2006; Rogers et al., 2000), however, few researches have explored improving students' abilities to solve electrochemistry problems. The ability of students to solve problems is called proficiency levels (Gunstone, 2015). The purpose of this research was to explore the effects of modeling teaching on students' proficiency in solving problems. The research questions were:

1. To what extent does modeling teaching improve students' proficiency in solving galvanic cell problems?
2. What are the advantages of modeling teaching in promoting galvanic cell problem solving?

Research Methodology

General Background

This research used a quasi-experimental research design to explore the effect of modeling teaching on improving students' proficiency in solving problems. The independent variable of the research was the teaching method. The students in the experimental class received modeling teaching, while those in the control class received lecturing teaching. The dependent variable was the performance level of students' abilities to solve galvanic cell problems. The developed galvanic cell proficiency measurement instrument was used to evaluate students' proficiency in solving the problem of galvanic cell. In addition, qualitative data were collected through unstructured interviews to obtain additional support for students' proficiency in galvanic cells. This research was conducted in the fall semester of 2017-2018 academic year. The research was carried out for one month (4 weeks).

Participants

The participants were students in two 11th grade classes in an ordinary upper-secondary school in Jinan, China; there were a total of 93 students aged 17-18. The school is located in the surrounding area of the city, and its students have a medium level of academic performance. Prior to the implementation, participants were informed of the purpose of the research and were told that their participation was voluntary, and that their test scores would be used independently without affecting their chemistry scores. All students in both classes volunteered to participate in the research.

Electrolytes, ionic reactions, and redox reactions related to galvanic cells were included in the final tests of the previous semester. An independent sample t test was performed on the final chemistry test scores of the last semester. The results showed that there was no statistically significant difference between the two classes ($t = -1.424, p > .05$). In order to exclude the effect of previous achievements and existing knowledge and experience on the dependent variables, the class with lower scores ($M = 76.62, SD = 11.15, N = 45$) as the experimental class (i.e., the class being administered modeling teaching), which included 27 boys and 18 girls, and the other class with higher scores ($M = 79.63, SD = 9.15, N = 48$) as the control class being administered teaching as usual, which included 30 boys and 18 girls.

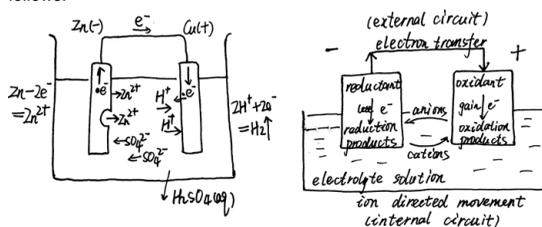


Teaching Intervention

The topic of galvanic cells in Chinese high school chemistry courses includes 3 content areas: the working principle of galvanic cells, the chemical power source and the corrosion and protection of metals. Students in both classes completed the above galvanic cell content in 2 weeks. The experimental class was taught using the modeling teaching program described above. The control class was taught using the same method as other classes that did not participate in the teaching experiment. The teacher taught three content areas in sequence using lecture-style teaching. Although the control class adopted the lecture-style teaching, this differed from full indoctrination teaching. The control class also designed some activities to promote students' active learning according to the teaching content and tasks (such as requiring students to do experiments and carry out discussions around problems). In the process of designing and implementing teaching, the teacher balanced the time for the two classes of students to experiment and participate in the discussion. Taking the content of "working principle of galvanic cells" as an example, the teaching process of the experimental class is shown in Table 1, and the teaching process of the control class is shown in Table 2.

Table 1
Modeling Teaching in the Experimental Class

Teaching step	Teacher's activities	Students' activities
Identifying elements	<ul style="list-style-type: none"> Requirement for assembly: copper-zinc dilute sulfuric acid single-liquid galvanic cells Ask questions: <ol style="list-style-type: none"> What are the necessary conditions (elements) for the formation of a galvanic cell? What role do the elements play in the current generation process of a galvanic cell? 	<ul style="list-style-type: none"> Conduct an experiment, observe experimental phenomena, analyze the characteristics of the composition of the galvanic cell Discuss the necessary conditions (elements) that constitute the galvanic cell and the role of the electrodes, electrolytes and redox reactions in the current generation process of the galvanic cell
Constructing models	<ul style="list-style-type: none"> c) How is the current generated in the copper-zinc dilute sulfuric acid single-liquid galvanic cell? Design task: draw a copper-zinc dilute sulfuric acid single-liquid galvanic cell model and a galvanic cell model Guide the students to reflect the phenomenon change on the macro level and the particle change on the micro level as much as possible when building the model of a copper-zinc dilute sulfuric acid single-liquid galvanic cell and use the chemical symbols to represent the process Analyze and evaluate the representative models constructed by students, show the galvanic cell model constructed by the teacher, and emphasize that this is just an example of the galvanic cell model. Any form that can characterize the galvanic cell elements and the relationship between the elements can be recognized 	<ul style="list-style-type: none"> Establish the connection between the elements based on the experimental facts, analyze the principle of current generation in the copper-zinc dilute sulfuric acid single-liquid galvanic cell, draw a model that can explain the working principle of a copper-zinc dilute sulfuric acid single-liquid galvanic cell, and summarize and abstract the galvanic cell model from the specific galvanic cell (Students will judge the electron flow from the zinc sheet to the copper sheet through the wire according to the direction of the deflection of the galvanometer pointer. According to the gradual dissolution of zinc flakes, it is judged that zinc's volatile electrons will undergo an oxidation reaction to act as a negative electrode. According to the occurrence of bubbles on the copper flakes, copper will be judged as a positive electrode.) Examples of copper-zinc dilute sulfuric acid single-liquid galvanic cell models and galvanic cell models established by students are as follows:



Note: The original language of the pictures is Chinese, and the pictures are translated into English provided that the original meaning is not changed.

Teaching step	Teacher's activities	Students' activities
Revising models	<ul style="list-style-type: none"> · Demonstration experiment: copper-zinc copper sulfate double-liquid galvanic cells d) Can the constructed galvanic cell model explain the working principle of this galvanic cell? 	<ul style="list-style-type: none"> · Watch the demonstration experiment · Use the constructed model to explain the working principle of the copper-zinc copper sulfate double-liquid galvanic cell and verify, reflect and revise the constructed model
Evaluating models	<ul style="list-style-type: none"> · Design situation: new energy-efficient vehicles rapidly become popular, while traditional vehicles encounter production and sales difficulties. · Task design: design a feasible battery device based on the battery reaction of a hydrogen energy electric car 	<ul style="list-style-type: none"> · Design and discuss the feasibility of the solution in groups, apply the constructed model to explain the working principle of the battery and evaluate the constructed model

Table 2*Lecturing Teaching in the Control Class*

Teaching step	Teacher's activities	Students' activities
Understanding the working principle of galvanic cells	<ul style="list-style-type: none"> · Requirement for assembly: copper-zinc dilute sulfuric acid single-liquid galvanic cells · Ask questions: <ol style="list-style-type: none"> a) How is energy converted during this process? b) What is the principle underlying current generation in a copper-zinc dilute sulfuric acid single-liquid galvanic cell? · Instruct: the working principle of the copper-zinc dilute sulfuric acid single-liquid galvanic cell (Under the action of potential difference, the electrons can move directionally to form a current. When zinc and copper are immersed in electrolyte solution at the same time, the two metals have different abilities to lose electrons. Zinc atoms are more likely to lose electrons than copper atoms. The electrons lost from the zinc atoms flow through the wire to the copper sheet, and Zn^{2+} enters the solution. The Cu^{2+} in solution gains electrons on the copper sheet and undergoes a reduction reaction, resulting in copper deposition on the copper sheet. Zinc flakes are both electrode materials and electrode reactions. In the galvanic cell, the copper sheet does not participate in the reaction. As a positive electrode material, the copper sheet plays a conductive role, and the copper sheet can also be replaced with an inert electrode. The directional movement of ions in the solution between the two poles and the directional movement of electrons in the external circuit constitute a closed loop, which makes the reaction of the two electrodes continue, thereby leading to an orderly electron transfer process and the generation of current.) 	<ul style="list-style-type: none"> · Conduct an experiment and record the experimental phenomena, recognize that galvanic cells convert chemical energy into electrical energy · Discuss the principle of copper-zinc dilute sulfuric acid single-liquid galvanic cell, try to write the equation representing the electrode reaction · Listen, think and record
Recognizing the salt bridge double-liquid galvanic cell	<ul style="list-style-type: none"> · Demonstration experiment: copper-zinc copper sulfate double-liquid galvanic cells · Ask questions: <ol style="list-style-type: none"> c) Is the galvanometer pointer deflected prior to salt bridge insertion? Is there any current generated after the salt bridge is inserted? What is the role of the salt bridge? d) Compared with copper-zinc dilute sulfuric acid single-liquid galvanic cell, what are the advantages of the double-liquid galvanic cell? · Instruct: the working principle of the double-liquid galvanic cell 	<ul style="list-style-type: none"> · Watch the demonstration experiment and record the experimental phenomena · Think and discuss in groups. (Understand that the salt bridge connects two isolated electrolyte solutions to conduct current. The two electrode reactions of the double-liquid galvanic cell are carried out under the condition of being separated from each other, Zn and Cu^{2+} are not in direct contact, and the energy conversion efficiency is improved.) · Listen and record
Class summary	<ul style="list-style-type: none"> · Summary <ol style="list-style-type: none"> a) The composition conditions for a galvanic cell b) Method for writing electrode reaction equations 	<ul style="list-style-type: none"> · Understand that electrodes, electrolytes, closed circuits and redox reactions are the constituent conditions of galvanic cells and master the writing skills of electrode reaction equations



The control class adopted a lecture-type instruction process that focused on relevant knowledge about galvanic cells, such as the composition conditions of galvanic cells, the working principle of galvanic cells, and writing electrode reactions. Teachers asked questions, instructed students to have discussions and conducted experiments according to the teaching content. The experimental class was taught with modeling teaching, which focused on the formation of a galvanic cell mental model in the students' minds, with the aim of enabling students to experience the modeling process. The students in the experimental class participated in a multi-round model construction process. First, they constructed a specific galvanic cell model of the copper-zinc single-liquid galvanic cell. Then, they constructed a model that could explain all galvanic cells by deepening their understanding of this specific galvanic cell model. Next, they analyzed and verified the abstract model, verifying the validity and deepening their understanding of the model. Finally, students were provided with an opportunity to apply the model to internalize their understanding of the model.

Process

Considering that it may be difficult for school teachers to carry out modeling teaching, the author of this article taught both classes. She has certain high school chemistry teaching experience and a deep understanding of the process of modeling teaching. The specific teaching lessons of the two classes are shown in Table 3. The purpose of lesson 4 "class exercise" is to improve students' ability to consolidate new knowledge after learning new content. The galvanic cell content learning, class exercise and teaching effect test on galvanic cells were conducted on the same day in both classes. To avoid any potential impacts of a change in the teacher on students' learning, the students in both classes were allowed to become familiar with the teacher's teaching style in the first two weeks of the galvanic cell teaching. In order to ensure that the teacher strictly followed the predetermined teaching procedures and strategies, the lecturer and the other researchers carefully studied and became familiar with the two teaching modes before the lecture to avoid the interference of subjective emotions and potential beliefs about the teaching. In the experiment, another researcher recorded and supervised the implementation of the teaching.

Table 3
The Arrangement of the Lessons on Galvanic Cells

Week	Lesson	Lesson	Experimental class	Control class
1	1	The working principle of galvanic cells	Modeling teaching	Lecturing teaching
	2	Chemical power source	Modeling teaching	Lecturing teaching
2	3	Corrosion and protection of metals	Modeling teaching	Lecturing teaching
	4	Class exercise		

During teaching, to mitigate the John Henry effect, the students were not told whether they were in the control class or the experimental class. After the completion of the galvanic cell teaching (starting in the third week), the teacher used the galvanic cell proficiency assessment tool to test the effect of the different teaching styles in both classes. The test time was 30 minutes, and the teacher supervised the whole process. After the test, all the copies were collected on time. Qualitative data were collected through unstructured interviews. A total of 8 students of different proficiency levels were interviewed in the two classes. All the students who participated in the interview agreed during the interview to its being recorded.

Instrument

The differences between the two classes in galvanic cell problem solving were examined by the instrument developed based on the Rasch model. In this measurement instrument, students' proficiency in solving galvanic cell problems is divided into three levels. The item consists of two forms: multiple-choice questions (Q1-Q7) and open questions (Q8-Q11). Each open item contains 1 to 4 subitems. For more information about this tool, please refer to the relevant literature (Lu et al., 2020). The tool was developed through two rounds of testing and passed both the expert test and the Rasch model test, with good content and structure validity.



Data Analysis

The Rasch model estimates both the difficulty of the item and the ability of the student and converts the individual's performance on the item to an equidistant logit value. By comparing logit values, a comparison between student abilities (proficiency in solving galvanic cell problems for the students in this research) can be achieved.

Research Results

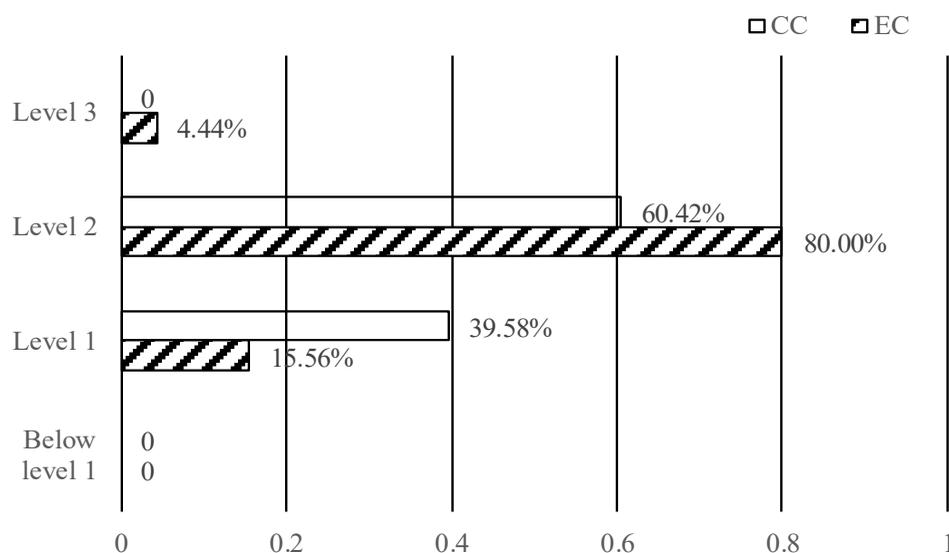
Differences in the Proficiency of Solving Galvanic Cell Problems

The research obtained the ability value (logit value) of all the students in the two classes to solve galvanic cell problems, and tested it using an independent sample t test. First, students' proficiency levels were compared between the two classes on the whole. The t test results showed that there was a significant difference in the problem-solving ability for galvanic cell problems between the two classes, $t_{(91)}=4.45, p < .01$. The experimental class ($M = 0.85, SD = 1.04$) was significantly better at solving galvanic cell problems than the control class ($M = -0.01, SD = 1.02$). This shows that modeling teaching has a positive impact on students' problem solving.

Second, the differences between the two classes in the three proficiency levels were compared. On the one hand, to count the proportion of students in the two classes at each of the three levels, the average measure value of all items corresponding to each level was defined as the proficiency threshold. The threshold value of level 1, level 2 and level 3 were calculated as -3.54, 0.06 and 3.57 respectively. Figure 2 shows the statistical results of the number of students with each proficiency level in the two classes according to the obtained threshold value. The vertical coordinate is the level, and the horizontal coordinate is the proportion of students at each level.

Figure 2

Distribution of Students in the Experimental Class (EC) and Control Class (CC) among the Three Levels



As can be seen in Figure 2, no students in either class fell below level 1. About 40% of the students in the control class were at level 1, far more than the 16% in the experimental class. The vast majority (80%) of students in the experimental class were at level 2. No student in the control class achieved level 3, while a few students in the experimental class did.

The ability values of the two classes at each level were also compared. The mean ability value of each class at each level were calculated. Table 4 shows the results of the difference test in the mean ability value of the students at each level. It can be seen from Table 4 that the average ability value of the students in the experimental class at



level 1 and level 2 is higher than that of the students in the control class, and the difference test results show that the performance of the students in the experimental class at level 2 ($M = 1.13$, $SD = 0.85$) is significantly better than the performance of the students at level 2 in the control class ($M = 0.51$, $SD = 0.52$), $t_{(91)} = 3.47$, $p < .01$.

Table 4

The Difference Test of the Proficiency Level between the Experimental Class and the Control Class

Level	EC (N=45)		CC (N=48)		t	p
	M	SD	M	SD		
L1	-0.69	0.39	-0.81	0.49	.59	.562
L2	1.13	0.85	0.51	0.52	3.47	.001

Level 2: Understanding the Working Principle of Galvanic Cells

As can be seen from Table 4, there was a significant difference in the performance of the students in the two classes at level 2. Table 5 shows the statistical results of the performance of the two classes at level 2. As can be seen from Table 5, students in the experimental class performed better than those in the control class for most items. Especially for Q4 and Q8.1, the performance of the experimental class was more outstanding (the mean difference was 0.16). As for Q10.3, the performance of the control class was slightly higher than that of the experimental class, indicating that lecture-style teaching can also help students solve this problem.

Table 5

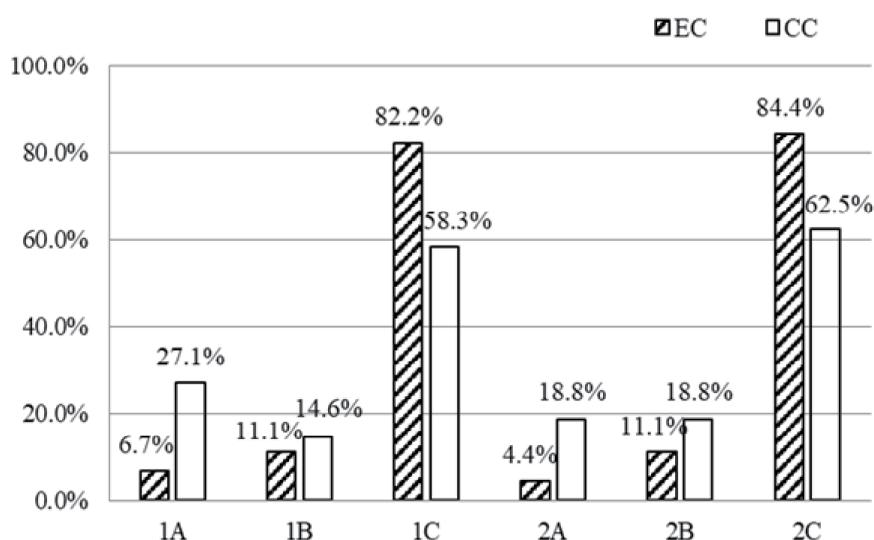
Statistics of the Performance of the Students in the Experimental Class and the Control Class for Level 2

Item	Mean of EC	Mean of CC	Difference of mean
Q2	0.82	0.78	0.04
Q4	0.74	0.58	0.16
Q7	0.66	0.54	0.12
Q8.1	0.91	0.75	0.16
Q8.2	0.92	0.86	0.06
Q10.1	0.32	0.24	0.08
Q10.2	0.19	0.08	0.11
Q10.3	0.54	0.56	-0.02
Q10.4	0.35	0.29	0.06

Q4 assesses students' understanding of spontaneous redox reactions. Q4 is a two-tier multiple-choice question, and the students' responses to the item are presented in Figure 3. In the first question, students are provided with three chemical reaction equations marked with enthalpy change, allowing students to choose a reaction that cannot theoretically be designed as a galvanic cell. Option A is a redox reaction and an endo-



thermic reaction, option B is a redox reaction but requires an initiation condition, and option C is the correct option for a nonredox reaction. The proportion of students who answered correctly in the experimental class (82.2%) was higher than that in the control class (58.3%). The second question asks about the reason for choosing the answer to the first question. Option A is “endothermic reactions cannot be designed as galvanic cells”, which was chosen by 4.4% of the students in the experimental class and 18.8% of the students in the control class. The experimental class had fewer students with this alternative conception than the control class. Option B is “the reaction that needs to be ignited cannot be designed as a galvanic cell”. Students in both the experimental class and the control class have the alternative conception, but compared with the control class (18.8%), the experimental class holds less of this conception (11.1%). This finding showed that compared with lecture teaching, modeling teaching can help students to correctly understand spontaneous redox reactions. In the experimental class, the proportion of students who answered correctly was higher, and the proportion of students with alternative conceptions was lower.

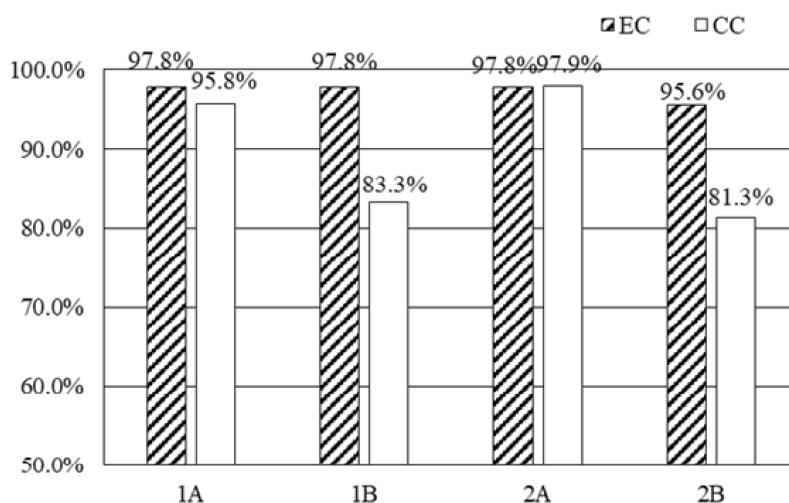
Figure 3*Q4 Item Responses*

Q8.1 assesses students' distinction between an electrode material and an electrode reactant. Q8.1 includes four sub questions on the measurement instrument. Students must correctly fill in the blanks for the negative electrode material, the negative electrode reactant, the positive electrode material, and the positive electrode reactant. The students' answers are shown in Figure 4. For the electrode materials of the positive and negative electrodes, students only needed the information in the question to correctly identify them, and almost all students in the two classes answered correctly. Regarding the determination of the electrode reactants of the negative and positive electrodes, a greater proportion of the experimental class students (97.8% and 95.6%, respectively) than control class students (83.3% and 81.3%, respectively) provided the correct answers, indicating that modeling teaching can enable more students to understand the working principle of galvanic cells and determine the substance involved in the reaction on the electrode.



Figure 4

Q8.1 Item Responses



Three students at level 2 in the experimental class were randomly selected for interviews. The results confirmed that those students who answered the items at level 2 correctly had achieved proficiency level 2 regarding galvanic cells and could understand the working principle of a galvanic cell, rather than just memorize the relevant knowledge about galvanic cells. The following demonstrates this phenomenon:

Interviewer: (Q8.1) How do you judge electrode materials and electrode reactants?

Chi: The electrode material is based on the activity of the metal, that is, the reduction of the metal, copper > silver, so copper is used as the negative electrode, and silver is used as the positive electrode. Before judging the electrode reactant, write the electrode reaction and the cell reaction. The total reaction in the device should be the replacement reaction of copper and silver ions. It is the negative electrode reactant that loses electrons, so copper is the negative electrode reactant. Silver ions get electrons at the positive electrode and are positive reactants.

Interviewer: (Q10.3) How do you judge the alkalinity enhancement of the positive electrode?

Hu: This requires writing the electrode reaction equation and looking at the changes in hydrogen ions or hydroxides around the electrode. ($\text{FeO}_4^{2-} + 3\text{e}^- + 4\text{H}_2\text{O} = \text{Fe}(\text{OH})_3 + 5\text{OH}^-$) Hydroxide ions are formed on the positive pole, and as the concentration of hydroxide ions in the solution increases, alkalinity increases.

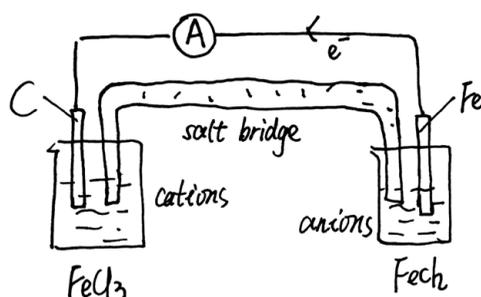
Level 3: Solving Chemical Problems Related to Galvanic Cells

The results in Figure 2 show that no students in the control class reached level 3, while 4.44% of students in the experimental class reached level 3—that is, two students reached level 3. It shows that it is difficult for students to solve the chemical problems.

Q9 examines the design of galvanic cell devices by students. The students needed to design a galvanic cell device based on $\text{Fe} + 2\text{FeCl}_3 = 3\text{FeCl}_2$. In all, 75.6% of the students in the experimental class got the correct answer, and 56.3% of the students in the control class got the correct answer. This finding shows that the students in the experimental class were better than those in the control class at solving the problem of designing the galvanic cell according to the cell reaction. Figure 5 shows the galvanic cell designed by Guo at level 3 of the experimental class.

Figure 5

Q9 Item Response of Guo



Note: The original language of the pictures is Chinese, and the pictures are translated into English provided that the original meaning is not changed.

Interviewer: How did you consider designing a double-liquid galvanic cell?

Guo: It can also be designed as a single-liquid galvanic cell. Their principle is the same, and they all conform to the galvanic cell model.

Interviewer: What role did the galvanic cell model play in solving this problem?

Guo: The galvanic cell model serves to separate the oxidation reaction and the reduction reaction in two places, and then the middle place can intercept the electric energy. In this reaction, iron loss electrons undergo oxidation reactions, corresponding to the negative electrode reactant in the model. Ferric divalent electrons are the oxidants, so they're the positive reactants.

Unlike the other items on the measurement instrument, Q11 is not a conventional galvanic cell test item, as it provides neither a cell reaction nor a galvanic cell diagram but only the background material of the fuel cell. Q11 assesses students' analysis of the fuel cell principle and related practical problems. The proportion of students who answered Q11.1, Q11.2 and Q11.3 correctly in the experimental and control classes were 6.7% and 2.1%, 0% and 0%, and 13.3% and 0%, respectively. Through interviews, we learned that the use of organic pentane to write electrode reaction equations and the introduction of the ZrO_2 crystal concept served as a major obstacle to students' problem solving, leading to poor performance on Q11.1 and Q11.2 in both classes. For Q11.3, we interviewed two students from the experimental class who answered correctly and found that the use of galvanic cell model could help students effectively solve this problem. The students identified the elements of fuel cells and successfully established a connection between the principle of fuel cells and the galvanic cell model:

Interviewer: Incomplete oxidation is the biggest defect of gasoline fuel cells. What can be produced during this process that can block gas passage? How do you think about it?

Zhang: We can first briefly analyze the following elements of this battery. The two electrodes are connected with air and gasoline vapor, and the total reaction should be the combustion reaction of pentane. ($C_5H_{12} + 8O_2 = 5CO_2 + 6H_2O$) The question is that the oxidation reaction is incomplete, so what needs to be considered is the reaction that occurs in the negative electrode. In this reaction, the negative electrode is the reducing agent pentane: if pentane is oxidized completely, carbon dioxide is produced; if not, it should be carbon.

Interviewer: Why not carbon monoxide?

Zhang: The substance blocking the gas channel is in a solid state, so it should be carbon particles.

Students' Views on Modeling Teaching

Informal interviews were also conducted to investigate the students' views on modeling teaching after experiencing the teaching intervention. The interview focused on two questions: the difference between the modeling teaching and the previous teaching, and whether the modeling teaching could help them understand the galvanic cell. Their interviews are as follows.



]Interviewer: Is the teaching of the galvanic cell theme the same as what you usually receive? If not, what is the difference?

Zhang: I constructed a galvanic cell model during class and then continued to modify it. I haven't built a model before in class.

Lu: Classrooms are not the same as usual, which is more interesting. We are all drawing our own models, and the models we draw do not need to be the same.

Interviewer: Does the learning method of generating a model help you understand the galvanic cell?

Hu: Well, it is very visual and very useful. It (the model) includes some important knowledge of the battery.

Lu: ... I did not understand the principle at the very beginning when I built the model, but when I encountered other galvanic cells, I would reconsider and modify them again....

Shi: Yes, although I have learned a lot about galvanic cells, their basic principles can be explained by galvanic cell models. For example, although lead storage batteries are very complicated, they can also be analyzed through it.

The results of the informal interviews show that the students in the experimental class had a positive view of modeling teaching. They thought of it as interesting and useful, including the most important knowledge of the cell, and the modeling process also gave them a deeper understanding of how the galvanic cell works.

Discussion

This research aims to explore whether modeling teaching promotes students' proficiency in solving problems. The results show that the experimental class ($M = 0.85$, $SD = 1.04$) students' proficiency in solving galvanic cell problems is significantly better than the control class ($M = -0.01$, $SD = 1.02$) at the 0.01 α level. The results of the unstructured interviews help explain the role of modeling teaching in facilitating students' efforts in solving galvanic cell problems.

Level 2 refers to "understanding the working principles of galvanic cells". The results show that students in the experimental class perform significantly better at level 2 than those in the control class. Compared with the control class, more students in the experimental class are at level 2, and they also perform significantly better at level 2 than those in the control class. Understanding concepts is an important factor in problem solving (Gabel & Bunce, 1994; Lee et al., 2001), and involving students in modeling has the potential to stimulate scientific understanding (Maia & Justi, 2009). Modeling teaching aims to improve students' proficiency by helping them deeply understand the working principles of galvanic cells. This is consistent with previous research results showing that modeling teaching can improve students' understanding of concepts (Cheng & Brown, 2015; Clement, 2008; Hestenes, 1995).

Justi and Gilbert pointed out that those who form mental models of existing consensus models, modify the existing models, or produce their own new model must be clear about the goal to be solved. The teaching and learning of the experimental class focused on the construction of galvanic cell models, and the purpose of this modeling was to explain the working principles of galvanic cells (how the current is generated in galvanic cells). Therefore, unlike lecture-style teaching, students learn a series of specific knowledge related to galvanic cells in a certain order. The classroom for modeling teaching begins with "current generation by galvanic cells"; and the questions, situations and activities in the classroom are all designed around this core principle; the purpose of the class is clearly to produce galvanic cell models, which can more effectively focus the learning and thinking activities of the students in the classroom so that students can think deeply about the working principles of galvanic cells.

The first step of modeling teaching is to identify the elements. Students not only need to understand and remember what the components of the model are but also need to know the role of each element in the operation of the model and the conditions to be a component. In the beginning of analyzing the elements of galvanic cells, students only know that galvanic cells include a metal rod and electrolytes. When they further analyze the role of galvanic cells in the process of generating a current, students will find that the metal rod (electrode material) and electrolytes do not necessarily participate in the cell reaction. Electrode materials and electrolytes are the transport media of electrons and ions, respectively, and whether or not they participate in the electrode reaction is determined according to the background of the cell. By correctly understanding the connotation, characteristics and functions of the elements, students will gain a deeper understanding of the concept of galvanic cells.



The proportion of students in the experimental class with alternative conceptions such as “the activity of the electrodes must be different” and “the electrodes must participate in the battery reaction” was less than the control class. This shows that modeling teaching can help students form a correct understanding of scientific concepts and change students’ alternative conceptions (Halloun & Hestenes, 1987; Wells et al., 1995).

Model-based conceptual learning follows the conceptual mental model construction process (Gobert & Buckley, 2000). Modeling teaching focuses on how to promote the construction, revision and development of personalized mental models in students’ minds; thus, this teaching approach is consistent with the conceptual modeling process recognized by the scientific community (Vosniadou & Brewer, 1992). Focusing on the transformation of students’ mental models in the process of learning can fundamentally alter the way students think (Yuan, 2009), thus efficiently and effectively transforming students’ alternative conceptions. The students in the experimental class participated in a multi-round model construction process. When students repeatedly draft scientific models, they inevitably analyze and modify their potential mental models (Bryce et al., 2016). After each round of modeling, the teacher required the students to express and communicate the model through drawing. Therefore, the teacher could also monitor the model content in the students’ minds, provide timely feedback and adjust their teaching to change the students’ incorrect ideas.

Level 3 examines students’ solutions to chemical problems. No students in the control class reached level 3, whereas a few students in the experimental class reached level 3. The experimental class performed better than the control class in designing galvanic cells and analyzing the incomplete oxidation reaction of gasoline fuel cells. The interview results help to explain that in the face of complex problems, the use of the constructed galvanic cell model can help students to recognize the nature of problems from complex and unfamiliar problem situations and find a breakthrough in solving such problems.

Modeling is essentially a special form of problem solving. On the one hand, the construction of models begins with real problems. On the other hand, the importance and applicability of a model can only be reflected through description, explanation, prediction and other deployment processes in the real world (Liu & Chiu, 2010). In the process of model revision and evaluation, teachers need to provide students with opportunities to verify the model and problem-solving activities in real situations. The experimental class used the dual-liquid galvanic cell with a salt bridge as a variant of modeling to promote students’ reflection on and modification of the galvanic cell models being built and provided students with an unfamiliar, real and complex situation of new energy-efficient vehicles upon which they could apply and evaluate the model they had constructed to learn to continuously improve and flexibly apply the model.

Wells et al. noted that an important reason for adopting the modeling method is to help students build a more coherent, flexible and systematic understanding (Wells et al., 1995). Constructing a model by determining the relationships between elements is a central step in modeling teaching. The students in the experimental class made a complete analysis of the generation of a current in galvanic cells by combining the elements, thereby breaking through the cognitive difficulty of “redox reactions separate but simultaneously” by allowing the students to understand the correlation between the elements and ways they interact. Therefore, the students remember not only isolated knowledge but also systematic, interrelated and interactive knowledge, allowing them to understand that the concepts are flexible and transferable. When encountering new situations and new problems, the students can more effectively identify the relationship between models and real problems, and skillfully use the modeling strategies learned in class to solve new and more complex problems.

In addition, as a constructive learning method (Maia & Justi, 2009), modeling can help students build knowledge of the world based on their existing experiences, and let students study the natural phenomena they want to understand. Students assume active learning and active construction in the learning process, personally experience the modeling practice activities of scientists, rather than passively accepting models constructed by others, and thus initiate inner learning mechanisms to stimulate their deep learning interests. The results of informal interviews show that students think that modeling teaching is very interesting and makes them have a deeper understanding of galvanic cells.

Conclusions and Limitations

Modeling teaching is believed to promote students’ understanding of scientific concepts. The results of this research further show that modeling teaching can not only improve students’ understanding of the



concept of galvanic cell, but also improve students' ability in solving galvanic cell problems. The proficiency of students in the experimental class in solving galvanic battery problems was significantly higher than that of the control class. Due to the lack of operational program structure, although many teachers realize the positive effect of modeling teaching, the application rate of teachers in the classroom is not high. The research has constructed a modeling teaching program structure that integrates modeling elements, teacher activities and student activities, helping teachers to promote the construction of students' internal mental models by clarifying operable external teaching events.

There are still some limitations to this research. This research constructed the modeling teaching program structure and tested its effect with using galvanic cells as an example. Although the results confirm the effectiveness of modeling teaching, more examples are needed to demonstrate the practical effects of the modeling teaching program structure. Second, although we have confirmed the role of modeling teaching in promoting students' proficiency in solving galvanic cell problems, modeling teaching has not helped more experimental class students reach the highest level (level 3). This may be related to the short time of the teaching intervention. Students had not received modeling teaching before; a longer time for the modeling teaching intervention might have been a better choice.

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