International Journal of Science Education and Teaching
Vol. 1, No. 2, pp. 96-120, May. – Aug. 2022
http://doi.org/10.14456/ijset.2022.10

Examining Senior High School Students' Ability in Constructing Scientific Explanation of Galvanic Cell

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Received: 14 Aug 2022 Revised: 31 Aug 2022 Accepted: 31 Aug 2022

Abstract. This study aimed at enhancing students' ability to construct scientific explanations of an electrochemistry content: galvanic cell. The teaching strategy was designed based on Vygotsky's (1978) internalization process, Johnstone's (1991) chemical representations, and two explanation models: the deductive nomological (DN) model proposed by Hempel and Oppenheim (1948) and the claim-evidence-reasoning (CER) model proposed by McNeill (2006). The critical action research processes were employed as the methodology by the first author researched on his teaching to do the self-study research and reflective-based research. Participants consist of fifty-nine students from two senior high schools in different academic years. Students' worksheets were analyzed to clarify their ability to construct scientific explanations. Also, classroom observations, student interviews, and opinions from two critical friends in each school were analyzed. The findings showed how students expressed their explanations through macroscopic, sub-microscopic, and symbolic representations. Likewise, the development of the educational media and the teaching strategy was shown.

Keywords: Scientific Explanation, Electrochemistry, Critical Action Research

INTRODUCTION

Literature review on senior high school electrochemistry education has revealed some problematic issues on this topic, such as misconceptions, misunderstandings, or no improvement of understanding (Rahayu, Treagust, & Chandrasegaran, 2021; Tien & Osman, 2017; Aydin, Friedrichsen, Boz, & Hanuscin, 2014; Brandriet & Bretz, 2014; Hamza, 2013; Rosenthal & Sanger, 2012; Hamza & Wickman, 2009; 2008; Potgieter, Harding, & Engelbrecht, 2008; Lee, 2007; Schmidt, Marohn, & Harrison, 2007; Bleicher, Tobin, & McRobbie, 2003; Schmidt & Volke, 2003; Ahtee et al., 2002; Sanger & Greenbowe, 2000; Ritchie, Tobin & Hook, 1997; Sanger & Greenbowe, 1997; Sanger, 1996). Electrochemistry also has been indicated as a complicated topic and a challenge for teaching and learning (Kempler, Boettcher, & Ardo, 2021; Supasorn, 2015; Ahtee, Asunta & Palm, 2002; Garnett & Treagust, 1992a; 1992b; Johnstone, 1991; Linford, 1961). These pedagogical difficulties should be solved. One important learning behavior that can indicate the achievement of students' learning is constructing an explanation of the scientific content they learned. Explaining ability has been stated as the central aim of learning science (Driver, Leach, Millar, and Scott, 1996). Students' explanatory works have been referred to as their evidence of understanding. Some national education agencies, e.g., the United States of America, have suggested that explanation is a significant core practice to improve science teaching and learning (National Research Council, 2012; Pashler et al., 2007). Besides, Finland's core curriculum has proposed that explanation is one principal method for chemistry instruction (Finish National Board of Education, 2003). Those have indicated that: explaining is a significant behavior that science teachers should promote to their students. This study, therefore, implements the developed instructional strategy fitted to the galvanic cell content to enhance students' ability to construct a scientific explanation.

THEORETICAL FRAMEWORKS

This study employed the Instructional Strategy designed for enhancing students' construction of scientific explanations proposed by Meedee and Yuenyong (2021). This instructional strategy has been backed by three theoretical frameworks: Vygotsky's (1978) internalization process. Second is Johnstone's (1991) three facets of content representations: macroscopic, sub-microscopic, and symbolic. The third is the two explanatory models: the Deductive Nomological (DN) proposed by Hempel and Oppenheim (1948) and the Claim-Evidence-Reasoning (CER) proposed by McNeill (2006). Based on those frameworks, the instructional strategy has been proposed in four stages. The details are illustrated in table 1; herewith, the codes of theoretical-based design play a role as the backing ideas of each stage.

Table 1 Stages of the instructional strategy and codes of theoretical based design

Stage	Descriptions	Codes of theoretical based design
Stage 1	**Action on Macroscopic Phenomena** A hands-on group experiment about the galvanic cell, an electrochemistry content, is provided. This activity expected students to learn the macroscopic phenomena they can observe directly.	A01
Stage 2	**Learn through Classifying the Three Representations**	
	1) Writing and Drawing to learn The *Writing-Drawing on the Chemical-Electrical Representations* (WDCER) Worksheet (see the Appendix A): the A4 size paper explicitly designed for the galvanic cell content is provided for every student to write and draw the findings from a group experiment. However, the direction on this worksheet is written in vocabularies that students are familiar with instead of science education terms such as macroscopic, sub-microscopic, or symbolic. Students have been expected to classify phenomena into three levels by individual forms rather than from their group summaries.	A01 A02
	2) Link all three representations The *Supporting Students' Understanding on Sub-microscopic phenomena* (SSUS) magnetic whiteboard: A media is specifically designed to help students link the sub-microscopic and symbolic representations they made to a macroscopic phenomenon observed from their group	A03 A04

Stage	Descriptions	Codes of theoretical based design
	experiment during stage 1. This media is made as a magnetic whiteboard to be stuck by the pictorial particle model sheets on that board; these model sheets can be moved because they are magnetic to represent the motion of particle levels, such as electrons in chemical reactions. Moreover, students can use magic markers to write or draw some more symbols or pictures. This board is expected to be educational material as a scaffolding to assist students in learning through classifying all three representations.	
	These activities are considered as the first step of Vygotsky's internalization process	B03
Stage 3	**Share Ideas between Group Discussions** The between-group discussion is the stage that provides a chance for all groups of students to present their classroom experiment findings. They had to show ideas about the three representations: macroscopic, sub-microscopic, and symbolic. This stage is considered the second step of Vygotsky's internalization process.	A04 B03
Stage 4	**Construct a Scientific Explanation** Students are assigned to make their scientific explanation on the galvanic cell content, formed as a paper-based written scaffold offered for every student: The Worksheet for *Supporting the Ability in Constructing Scientific Explanation* (SACSE): see the Appendix B. Designing this written scaffolding is based on the abovementioned models: CER and DN explanation models through logical deduction. Students need to do this paper individually, which is the third step of Vygotsky's internalization process.	B01 B02 B03

As table 1, the strategy has been proposed as four stages: Stage 1: Action on macroscopic phenomena. Stage 2: Learn through classifying the three representations. Stage 3: Share ideas between group discussions. Stage 4: Construct a scientific explanation. Each stage has the theoretical frameworks backing each learning activity. Those theoretical frameworks consist of two parts: Part A Learn through the chemical representations and Part B Constructing scientific explanations. Both parts are illustrated as seven abbreviation codes in table 1: A01-A04 and B01-B03. The details are shown below.

Part A: Learn through the chemical representations

A01 The roles of doing classroom experiments to serve the three facets of chemical representations

A classroom experiment has been designed as a hands-on activity. This activity has been planned to provide opportunities for students: (1) Record the macroscopic as writing and drawing. (2) Draw some pictures for the sub-microscopic. (3) Write some alphabet to represent symbolic phenomena.

This galvanic cell experiment is expected to be the activities shown for all three representational phenomena during once classroom learning period.

A02 The sequence used of the three facets of chemical representations

Based on Johnstone's (1991) critiques, his idea was challenging for students who were novices to learn new science content because of the occurrence at the same time of such three phenomena. To assist students in learning electrochemistry more accessible, the idea of Lin, Son, and Rudd II (2016), therefore, has been referred to as the backing idea of teaching strategy. They look at the chemical representations as to the different concreteness and abstractness. This idea is displayed in the figure below.

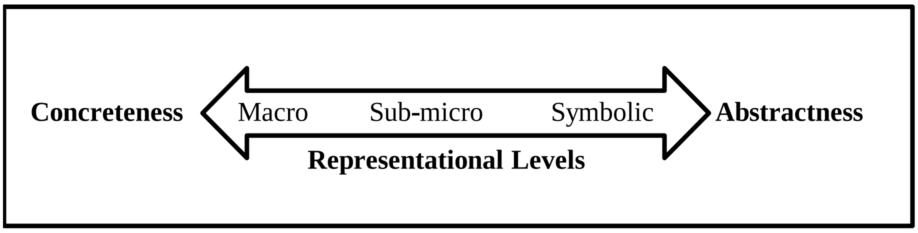


Figure 1 The concept of three-level (macroscopic, sub-microscopic, and symbolic) chemical representations is clarified by concreteness-abstractness of phenomena

As figure 1, the macroscopic, sub-microscopic, and symbolic representations are interpreted based on the concrete idea to abstract parallelly. Lin, Son, and Rudd II (2016) assumed that macroscopic was the most concrete phenomenon, sub-microscopic was moderate, and symbolic was the most abstract phenomenon. Their findings suggested that the effective sequence way of students' learning should be started from concrete to abstract.

Therefore, the instructional strategy designed for this study has provided students with learning at the macroscopic first. They were assigned to do a classroom experiment to observe directly and visibly. Then, they had to study the atomic and particle phenomena to respond to the idea of a sub-microscopic representation; the appropriated educational media (WDCER worksheet) was added to promote students' understanding of representing the sub-microscopic phenomena. Finally, learning about symbolic representation would be provided respectively.

A03 Media as educational stuff designed to support learners link sub-microscopic and symbolic representations to macroscopic phenomena

A macroscopic representation can be observed simply more than the other two facets. Linking the concepts of sub-microscopic and symbolic phenomena to macroscopic at the same time may become a difficulty for students who are novices. Two kinds of media were offered to solve students' encountering. The WDCER worksheet was given to students individually during a hands-on experiment. After completing a hands-on experiment, the SSUS magnetic whiteboard was given one board per group. This whiteboard has been expected to be the educational stuff as a scaffolding to help students learn through classifying all three representations. Moving and sticking the pictorial particle model sheets on the magnetic whiteboard together with writing and drawing some symbols could support the discussion process in each group. Moreover, they could use it to present their experiment findings to others.

A04 Roles of collaborative discussions from 1) the more capable peers and 2) the teacher's guidance during academic communications.

Based on Vygotsky's zone of proximal development, which concentrates on social interactions that support the human learning process. This idea believes that scholarly communication is essential in the classroom's teaching and learning. Communication may occur in many facets; however, a collaborative discussion is considered easy in the classroom because it can be conducted immediately if scientific issues arise during classroom learning activities. This collaborative discussion process for a student is provided in two dimensions: discussion with more capable peers and with teachers' guidance. von Glaserfeld (1993) also stated the benefit of classroom communication:

explaining something to a peer usually leads one to perceive more clearly. Therefore, capable peers and a teacher were set to be scaffoldings for bridging students' zone of proximal development.

Part B: Constructing scientific explanations

B01 Roles of the scaffolding particularly designed for the galvanic cell content

This study has aimed students to generate explanations scientifically for an electrochemistry content: galvanic cell. Writing and drawing were the primary modes to express explanations as paper-based: the SACSE worksheet. This worksheet suggested a structure to promote students' expressing an explanation. For instance, the blank lines were provided for a written mode, while the blank boxes for drawing mode.

Those lines and boxes were arranged in the worksheet based on the logical deductive method of the DN explanation model, which has oriented that the explainers should start with a general summary of an electrochemistry phenomenon. They need to add some more supporting details. Then, they need to give data and information as personal evidence to support that claim based on chemical representations, i.e., macroscopic, sub-microscopic, and symbolic. Finally, students must express their reasons for linking the evidence to that claim. This logical deductive way of explaining also accords to the CER model; it suggests that students begin proposing a Claim.

The educational scaffolding worksheet was designed as individual paper per person to serve the concept of Vygotsky's internalization process; details are in the following topic B03. This scaffolding was a suitable assisting tool to help students explain electrochemical phenomena scientifically based on their meaning-making through classroom activities. However, this scaffolding should be moved out gradually after students are more strong ability to construct explanations.

B02 Effects of students' making the meanings through the representations for explanations

Johnstone' representations have been considered a significant influence on chemistry (Taber, 2013a; 2013b; Talanquer, 2011; Gilbert & Treagust, 2009) and also a unique notion for research in chemistry education effectively (Wu & Yeziersk, 2022; Kelly, Akaygun, Hansen, Villalta-Cerdas, & Adam, 2021; Matijašević, Korolija & Mandić, 2016; Rau, 2015; Taskin, Bernholt, & Parchmann, 2015; Adadan, 2014; Dumon & Mzoughi-Khadhraoui, 2014; Lewthwaite, 2014; Philipp, Johnson, & Yezierski, 2014; Dangur, Avargil, Peskin, & Dori, 2014; Lewis & Bodner, 2013; Antonoglou, Charistos, & Sigalas, 2011). Therefore, it has been used to support students in constructing chemical explanations.

The concept of representations is set as a central idea to clarify electrochemical phenomena into three aspects of the claims, e.g., macroscopic claim, sub-microscopic claim, and symbolic claim (see a triangle in figure 2). Then, each claim must be supported by the scientific evidence sufficiently. In order to link those evidence to the claims, reasoning must be provided logically, which in this study proposes the deductive method based on the essay of Hempel and Oppenheim (1948). The whole relational process in figure 2 is considered the theoretical framework that will be used as the basic concept for developing an instructional strategy for enhancing students' construction of scientific explanations in the electrochemistry of this study.

Although this framework is considered a benefit for the study of explanation ability, employing it in classroom teaching should be concerned with providing strategies for individual construction of knowledge. Vygotsky's internalization process, therefore, needs to be discussed.

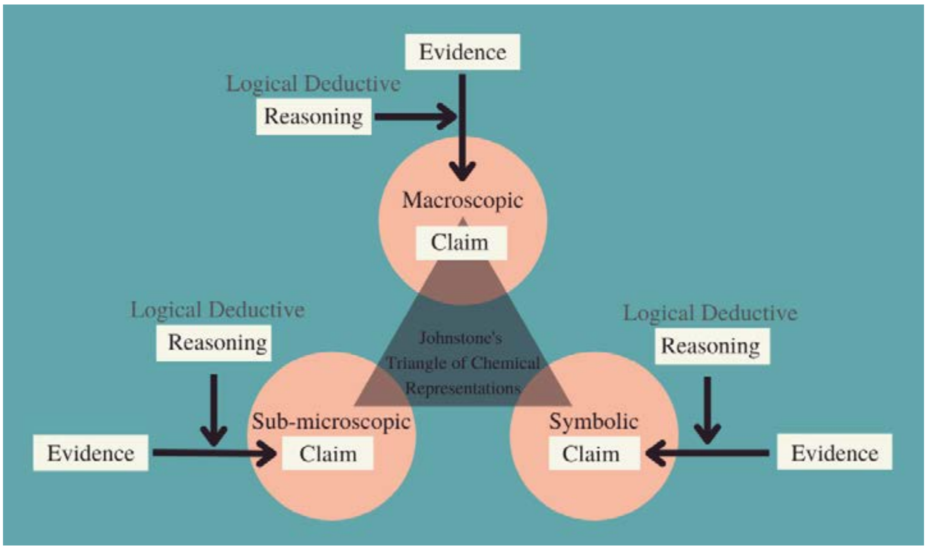


Figure 2 Theoretical framework to measure students' scientific explanation ability using the multi-faceted content representations reinforces the DN and CER explanatory models.

B03 Roles of the three steps of Vygotsky's internalization process

The supporting process of constructing an explanation of this study has employed the three internalization processes proposed by Vygotsky (1978). After students encounter the *new sign-using activity* (p.57), which can be illustrated as the new electrochemistry concept provided in the classroom, then (1) an external activity is reconstructed and begins to occur internally. Students were assigned to do the classroom experiment at this stage; this activity can be illustrated as the external activity of the internalization process. In the case of this study, it is stage 1: action on macroscopic phenomena.

(2) An interpersonal process is transformed into an intrapersonal one. This second step can be illustrated as stage 2 and stage 3 of this study, i.e., after finishing the interpersonal process in stage 1, students need to learn by classifying the three representations as a personal assignment, the intrapersonal process. (3) transforming an interpersonal process into an intrapersonal one results from a long series of developmental events. This third step can be illustrated as stage 4 of the instructional strategy of this study. After finishing a personal assignment of classifying the three representations, all groups in the classroom are persuaded to share ideas (stage 3) about their learnings (each group chose different chemicals or metals). Then, they must construct an explanation (stage 4) as a personal activity.

These three internalization steps are dialogues generated from personal inner speeches and thoughts; related to psychological and linguistic interactions (Bruner, 1962). This process is different from other kinds - cognitive and radical - of constructivism. Especially behaviorism that its approaches ignore the complexities of the internal psychological process (Wertsch & Stone, 1985), which is formed by each person's characteristics and experiences. However, the findings of this study would back up that this instructional strategy could encourage students' ability to construct scientific explanations of electrochemistry.

METHODOLOGY

The reflective-based and self-study research had been operated for this study, i.e., the first author performed a chemistry teacher role and studied his teaching. The critical action research process: plan, act, observe, reflect, proposed by Kemmis, McTaggart, and Nixon (2013), was used as a core concept to implement this instructional strategy in the science classroom, including collecting the data and analyzing the classroom phenomena.

Participants

Participants of this study were senior high school students from two schools in the same province in Thailand but in different districts (35 kilometers far from each other's). School 1 and School 2 students were same level of achievement ability because they Both are not different levels defined by the science national test score, but school 1 had a slightly higher average mean score than school 2.

School 1 was the eleventh-grade students in semester 2 of 2017 (November 2017-March 2018). School 2 was the twelfth-grade students in semester 1 of 2018 (May-September 2018). There were 40 students in School 1, and only 30 students had attended all three periods (all four stages of the instructional strategy). While the number of students in school 2 is 35, only 29 students had thoroughly attended. Thus, the total number of participants is 59 students.

Because of privacy, this essay has avoided declaring names and genders. So, they all will be called other codes. For example, a student who is a number 1 of school 2 will be called Sc2No01; likewise, a student who is a number 2 will be called Sc2No02, and others will be called like this respectively until the last number who will be called Sc2No35.

Furthermore, the critical reflective peers were conducted during the steps of observing, reflecting, and re-planning as a method to back the study's trustworthiness. A critical reflective peer in School 1 has graduated with a Master of Science (M.S.) in Chemistry for Teacher and has 12 years of experience as a chemistry teacher. While a critical peer in School 2 has graduated with a Doctor of Philosophy (Ph.D.) in Educational Research and Evaluation and has 14 years of experience as a chemistry teacher. Their suggestions were beneficial for improving learning activities of this study significantly. This method of peer debriefing process is one of five elements to make research's credibility which is the parallel of the internal validity (Lincoln & Guba, 1985; Guba & Lincoln, 1989; Erlandson, Harris, Skipper, & Allen, 1993).

Implementing the four stages in the electrochemistry classroom

This content, galvanic cell, was taught in three periods (50 minutes/period) through the four stages of this instructional strategy as shown in Table 1. Stages 1-3 were managed for two consecutive periods on the same day. While stage 4 was managed for one period on another day but the same week. In stages 1-3, the electrodes, and electrolytic solutions in stages 1-3 were used several elements such as Aluminium: $Al(s)|Al^{3+}(aq)$, Copper: $Cu(s)|Cu^{2+}(aq)$, Magnesium: $Mg(s)|Mg^{2+}(aq)$, and Zinc: $Zn(s)|Zn^{2+}(aq)$ which students could choose and pair independently on condition that the electrolytic solutions must fit the electrodes but, in stage 4, they were asked merely copper and zinc to explain the production of electric current from a redox (reduction and oxidation) reaction.

Data collection and analysis

Translating the worksheets that students constructed their scientific explanations has been used the major and minor elements proposed by Meedee and Yuenyong (2021) as table 2. The major element contains claim, evidence, and logical deductive reasoning based on the DN and CER explanation models proposed by Hempel and Oppenheim (1948) and McNeill (2006). The minor element contains the three chemistry content representations proposed by Johnstone (1991): macroscopic, sub-microscopic, and symbolic. These elements are the basic structure to measure the students' explaining ability of this study through the rubric score specific to this electrochemistry content: galvanic cell (see the Appendix C).

Table 2 The major and minor elements of the specific rubric score for analyzing the explanation ability, codes for analyzing, and score of each element

Major Elements	Minor Elements	Codes for Analyzing	Total Scores
C: Claim	-	C	2
E: Evidence	Ma: Macroscopic	MaE	3
	Su: Sub-microscopic	SuE	3
	Sy: Symbolic	SyE	3
R: Reasoning as logical deduction	Ma: Macroscopic Su: Sub-microscopic Sy: Symbolic	R	4
Total		2C-(3Ma-3Su-3Sy)E-4R = 15	

As table 1, the Claim is abbreviated as C, and the total score is 2. The Evidence is abbreviated as E and is split into three sub-elements: macroscopic evidence, sub-microscopic evidence, and symbolic evidence. The total score of each sub-element is 3 points, resulting in the total score of E being 9. Thirdly, the Reasoning is abbreviated as R, and the total score is 4. Students who could express their full explaining score would get the category of 2C-(3Ma-3Su-3Sy)E-4R, of which the total score is 15.

FINDINGS

The findings revealed what we learned from action research for students' scientific explanation ability in learning about galvanic. The section will clarify the examining categories of students' scientific explanation ability and then discuss what we learned to change teaching and issues of improving students' scientific explanation ability.

1. Categories of students' scientific explanation ability

After we finished all three periods of the four stages of the instructional strategy, the students' worksheets for SACSE were scored to represent the ability to construct a scientific explanation for galvanic cells. Those scores as the categories of two schools are shown in table 3.

Table 3 shows that eight students could get a full score of the 2C-(3Ma-3Su-3Sy)E-4R category after learning this instructional strategy. In addition, 79.66% of all students scored more than 10 points (48 students: school 1 = 28, school 2 = 19), whereas merely 20.34% scored no more than 10 points (12 students: school 1 = 2, school 2 = 10).

Besides, students from both schools expressed their explanations in 22 categories: 11 for school 1 and 14 for school 2. Most students (93.33%) could provide all five of the explanatory elements in table 1: C, MaE, SuE, SyE, and R. There were merely four students (6.66%) who still were not complete in providing fully.

According to the results of students' scientific explanations in table 3, the researchers and colleagues reflected on how to improve students' abilities. The reflection was developed through the after-teaching reflection, students' tasks, and student interviews. This reflection allowed us to learn what and how to increase students' scientific explanation ability in learning about galvanic as following issues.

Table 3 Frequency of students' categories of scientific explanation ability and frequency of students in each category

Scores	Categories of students' scientific explanation ability [2C-(3Ma-3Su-3Sy)E-4R=15]	Frequency of students		Frequency of two schools' students (%)
		School 1	School 2	
15	2C-(3Ma-3Su-3Sy)E-4R	6	2	47 (79.66)
14	2C-(3Ma-3Su-3Sy)E-3R	5	4	
13	2C-(3Ma-3Su-3Sy)E-2R	1		
	2C-(3Ma-2Su-3Sy)E-3R	8		
	2C-(2Ma-2Su-3Sy)E-4R	2		
	2C-(2Ma-3Su-3Sy)E-3R		1	
	2C-(3Ma-3Su-3Sy)E-2R		2	
12	2C-(3Ma-2Su-3Sy)E-2R	2		
	2C-(3Ma-1Su-3Sy)E-3R	2		
	2C-(2Ma-3Su-3Sy)E-2R		2	
11	2C-(2Ma-2Su-3Sy)E-2R	1	8	
	2C-(2Ma-1Su-3Sy)E-3R	1		
10	2C-(1Ma-1Su-3Sy)E-3R	1		12 (20.34)
	2C-(1Ma-2Su-3Sy)E-2R		3	
	2C-(2Ma-2Su-1Sy)E-3R		1	
	2C-(3Ma-3Su)E-2R		1	
9	2C-(1Ma-2Su-1Sy)E-3R		1	
	2C-(1Ma-3Su-2Sy)E-1R		1	
	2C-(2Ma-3Su)E-2R		1	
8	2C-(1Ma-1Su-2Sy)E-2R	1		
7	2C-(2Ma-2Su)E-1R		1	
4	2C-(1Ma-1Su)E		1	
Total	22 categories School 1=11, School 2=14	30	29	59 (100.00)
		59		

2. What we learned how to improve students' scientific explanation ability

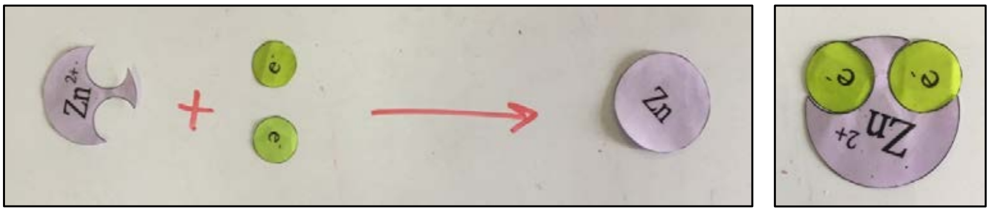
The teaching about galvanic in two schools suggested that the researchers learn some issues for improving students' scientific explanation ability. These included:

- Improving the sub-microscopic media via the atomic and ionic sizes-based design
- Pictorial sub-microscopic evidence for supporting scientific explanations
- Adjusting the stages of the instructional strategy

Each issue will be discussed below.

Improving the sub-microscopic media: via the atomic and ionic sizes-based design

During school 1's students were sharing their ideas in a whole-class discussion of stage 3; the first author, as a chemistry teacher, noticed that some of them said: *"the dented atom"* to represent an ion in their group SSUS magnetic whiteboard. This word made us realize that the educational media might mislead them. A sample of students' works on the whiteboard is shown in figure 3.



A reaction of: $Zn^{2+}(aq) + 2e^{-} \rightarrow Zn(s)$ "*analogy as a frog*"

Figure 3 Some students' works from the activity of the SSUS magnetic whiteboard

In figure 3, A student (Sc1No06) described his/her group magnetic whiteboard: (1) *"this dented atom of zinc gains 2 electrons; it will become a full atom like this"*. (2) *"if we move green electrons into the dented positions of an ion, it will change to be the normal atom, not be the ion anymore. Its shape is like a frog"*. This sentence made everyone laugh, including a reflective peer. However, as the teacher roles, the first author realized that this might form misconceptions in learning. This error was like Kelly, Barrera, and Mohamed's (2010) findings that found the misconceptions in sub-microscopic from undergraduate students. Gkitzia, Salta, & Tzougraki (2020) also found that students got problems with solid-state particle structure. In addition, the mistake of these model sheets was also liked the study of Rosenthal & Sanger (2012) that misconception came from their media: the computer animation.

Likewise, analyzing in school 1 students' scientific explanation ability focusing on three types of evidence, the sub-microscopic (SuE) was the lowest average mean score compared to other elements, see table 4 and figure 4. This lack indicated that there were some problems in this element.

Table 4 School 1's scientific explanation ability mean scores, standard deviations, and percentage compared to the full scores of each element

Elements	C	E			R
		MaE	SuE	SyE	
Mean	2.00	2.73	2.23	2.97	3.10
(SD)	(0.00)	(0.58)	(0.73)	(0.18)	(0.66)
%*	100	91.11	74.44	98.89	77.50

%* = Percentages compared to the full scores of each element
SD = Standard deviations

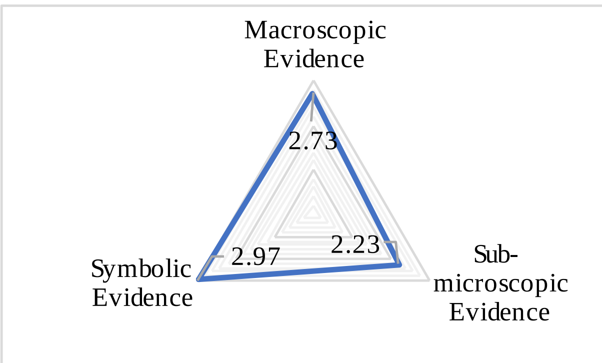


Figure 4 School 1's scientific explanation ability mean score of macroscopic, sub-microscopic, and symbolic evidence

Therefore, we (a school 1 critical friend and the first author) interpreted on students' providing sub-microscopic evidence that their analogy of the SSUS magnetic whiteboard's model sheets (as a frog) was the misconception about atomic/ionic sizes and radii. This mistake could spread to other students. So, the first author immediately confessed to them all that: these dented ions were wrong. Thus, we decided to cancel those dented model sheets for the subsequent action research cycle.

Regarding sizes and radii, almost all elements in senior high school electrochemistry are often metals. Those metallic elements will regularly lose some electrons rather than gain electrons, becoming the positive charge ions: cations. Those cations are smaller than their parent atoms. Hence, the atomic model sheets had been revised based on the concept of the atomic sizes that would increase when gaining electrons and decrease when losing electrons. A sample of the model sheets is illustrated as actual sizes for A4 paper printing; details are in figure 5.

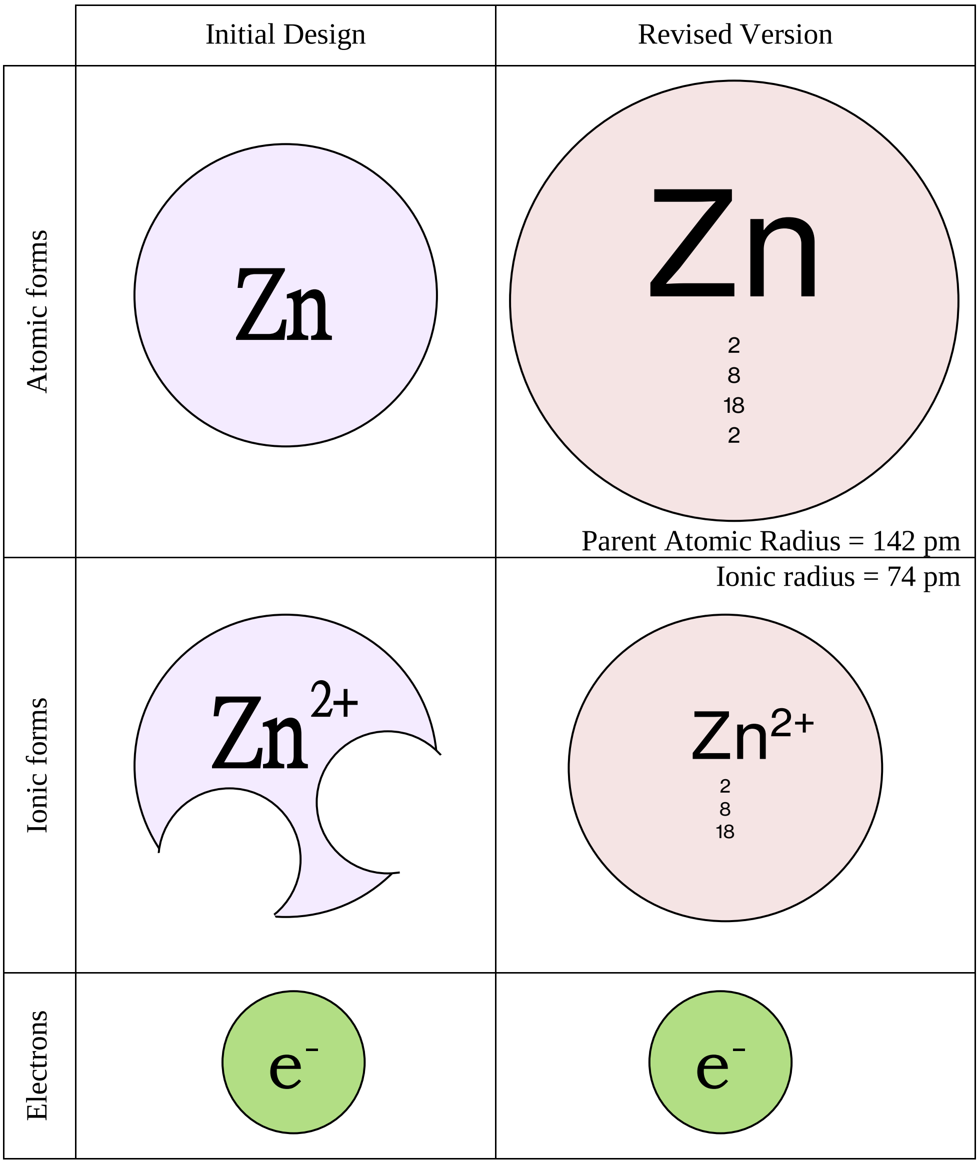


Figure 5 The atomic and ionic model sheets that are adjusted based on the concept of atomic size and radii, and electron configuration. (Real sizes for A4 paper printing)

In figure 5, the Initial Design of a zinc atom and its ion is in the first column: the radius of atomic and ionic forms are the same size without considering the actual sizes that each is different. In this design, the ionic form made a difference to its parent atoms by (1) adding the two-plus symbol, becoming Zn^{2+}, and (2) making the model sheets as the two holes fit an electron model (green) sheet size. While the Revised Version of those model sheets generated the atomic and ionic forms as different sizes based on the scientific data, the atomic radius of Zn is 142 Picometers which is bigger than the ionic radius of Zn^{2+}: 74 Picometers [LibreTexts.org: Brown, LeMay, Bursten, Murphy, & Woodward (2022)]. Moreover, both forms have been added to their simple electron configurations to clarify the number of electron shells or energy levels.

In the case of the zinc atom: 30 electrons, there are four shells of $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $4s^2$ $3d^{10}$ in ascending order of orbital energies or [2 8 18 2] in the simple form. In the ionic form, zinc loses 2 electrons to form Zn^{2+}, so removing 2 electrons from the $4s^2$ becomes 28. Its electron configuration can be shown as $1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^6$ $3d^{10}$ or [2 8 18] in the simple form. Students were expected to notice those numbers of shells; readily, they should notice that Zn was bigger than Zn^{2+} because of their number of electrons' shells, i.e., Zn loses 2 electrons of its valence shell, resulting in only three shells remaining.

After employing this revision of model sheets for use in the SSUS magnetic whiteboard, the school 2 students' sub-microscopic misconceptions were not found during either the observation or reflection steps of the action research process.

Besides, in stage 2 of this instructional strategy, a concept of the different sizes of ions and their parent atoms appeared in the WDCER worksheet. Students represented the electrochemical phenomena by displaying the electron transferring both anode and cathode, which is related to the size-changing of particles. The sample is shown in figure 6, which is the work of a Sc2No12 student.

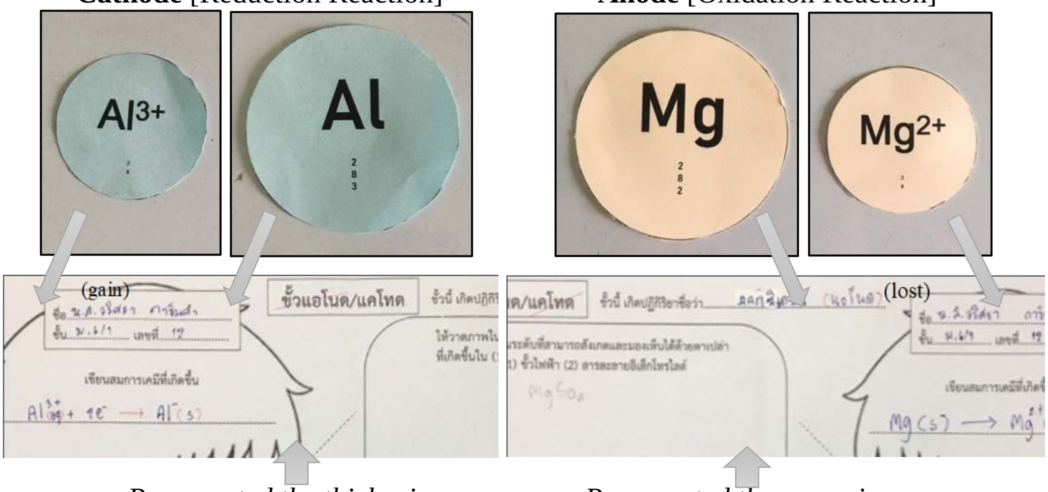


Figure 6 The Sc2No12 student's using the concept of the electron configuration from the revising version of model sheets to link macroscopic to sub-microscopic phenomena.

In figure 6, a Sc2No12 student got 14 points for the explaining ability as a category of 2C-(3Ma-3Su-3Sy)E-3R. S/he expressed sub-microscopic ideas by writing and drawing the simple electron configurations of aluminum and magnesium to clarify:

(1) The *thickening* of aluminum metal in the cathode was the reduction reaction by illustrating a puffed area; see a bottom left arrow. S/he drew five or six small circles to represent an area of aluminum metal dipped in the electrolytic solution thicker than before they started the experiment, which is a macroscopic phenomenon; they experimented with in stage 1 of the instructional strategy. Based on scientific data, Al^{3+} ions in the liquid electrolytic solution of aluminum sulfate [$Al_2(SO_4)_3$] gain three electrons, becoming the solid state of aluminum metal. These can be written as a chemical reaction as [$Al^{3+}(aq) + 3e^- \rightarrow Al(s)$] which s/he could write correctly. Both $Al^{3+}(aq)$ and Al(s) were represented by marking a vertical ellipse around the simple electron configurations of each: Al^{3+} = 2 8

and Al = 2 8 3 respectively. [Note: However, there is a misconception about the number of losing electrons which is $3e^-$, should not be $2e^-$ like s/he wrote].

(2) The magnesium metal's *corrosion* in the anode was the oxidation reaction; see the bottom right arrow. S/he made a hole in a group of small circles to represent a dented area of aluminum metal dipped in the electrolytic solution. This metal corroded, a macroscopic phenomenon they experimented with in stage 1. Based on scientific data, the magnesium metal [Mg(s)] lost two electrons, becoming Mg^{2+}(aq) ions; all are in the liquid electrolytic solution of magnesium sulfate [$MgSO_4$]. These can be written as a chemical reaction as [$Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$] which s/he could write correctly. Both Mg^{2+}(aq) and Mg(s) were represented by marking a vertical ellipse around the simple electron configurations of each: Mg^{2+} = 2 8 and Mg = 2 8 2, respectively.

These findings that students applied the concept of atomic/ionic sizes, the electron configuration, and the flow of electrons to clarify the occurrences of electric current have indicated the benefits of the SSUS whiteboard as a scaffolding media to encourage students' learning in a sub-microscopic phenomenon. These accord with the study of Berg, Orraryd, Pettersson, & Hultén (2019), which assigned students to make physical models of sub-microscopic particles for equitable chemical reasoning.

We would propose that this educational media's new design could benefit students to understand the scientific phenomena of the size-changing of an atom and its ion more closely. Also, it has significantly played a role as a tool to assist students can represent the particle levels as the sets of evidence to support their explanations. Hence, the students' sub-microscopic evidence would be focused on.

Pictorial sub-microscopic evidence for supporting scientific explanations

After we finished all three periods of the four stages of the instructional strategy, SACSE worksheets (details were in table 1 and Appendix B) from all 59 students were analyzed on their sub-microscopic evidence. Findings are shown in table 5.

In table 5, 50 students (84.75%) represented their ideas of sub-microscopic by making the pictorial mode and the written mode: the major group. In comparison, 9 students (15.25%) used the inappropriate pictorial mode to support their scientific explanations: the minor group. In the minor group, 3 students made inappropriate pictures but were good at writing, and 6 showed inappropriate evidence in both pictorial and written modes. We did not find students expressing their sub-microscopic ideas by a single mode of writing or drawing.

Comparisons of average mean scores of explaining ability between two groups of students who illustrated sub-microscopic evidence by (1) using pictorial mode and (2) using inappropriate pictorial mode were shown in figure 7.

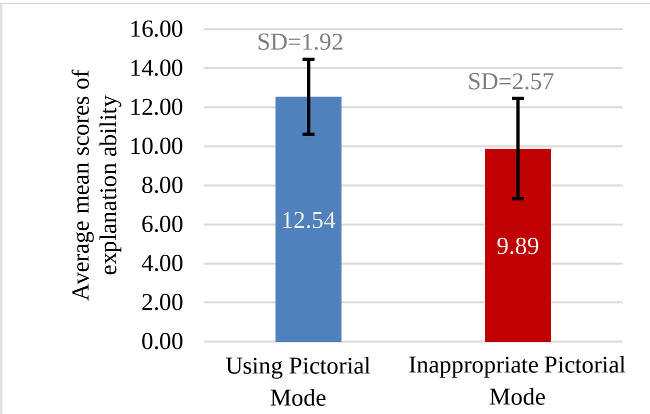


Figure 7 Average mean scores and standard deviations (SD) of the explanation ability divided by two group of students who illustrated sub-microscopic evidence by (1) using pictorial mode and (2) making inappropriate pictorial mode

Table 5 Frequencies and percentages of students in types of pictorial sub-microscopic evidence

Types of Pictorial Sub-microscopic Evidence			Scores	Categories	F		Total (%)	Grand total (%)
					Sc 1	Sc 2		
Using pictorial mode	I	Chemical Equation pictorial	15	2C-(3Ma-3Su-3Sy)E-4R	3		15 (25.42)	50 (84.75)
			14	2C-(3Ma-3Su-3Sy)E-3R	3			
			13	2C-(3Ma-2Su-3Sy)E-3R	7			
				2C-(2Ma-2Su-3Sy)E-4R	1			
			12	2C-(3Ma-2Su-3Sy)E-2R	1			
	II	Dynamic pictorial	15	2C-(3Ma-3Su-3Sy)E-4R	1		15 (25.42)	
			14	2C-(3Ma-3Su-3Sy)E-3R	1	1		
			13	2C-(3Ma-3Su-3Sy)E-2R	1			
				2C-(3Ma-2Su-3Sy)E-3R	1			
				2C-(2Ma-3Su-3Sy)E-3R		1		
			12	2C-(2Ma-3Su-3Sy)E-2R		1		
			11	2C-(2Ma-2Su-3Sy)E-2R	1	5		
			10	2C-(2Ma-2Su-1Sy)E-3R		1		
			9	2C-(1Ma-2Su-1Sy)E-3R		1		
	III	Macroscopic pictorial	14	2C-(3Ma-3Su-3Sy)E-3R		2	8 (13.56)	
			13	2C-(3Ma-3Su-3Sy)E-2R		1		
			11	2C-(2Ma-2Su-3Sy)E-2R		3		
			10	2C-(1Ma-2Su-3Sy)E-2R		1		
			7	2C-(2Ma-2Su)E-1R		1		
	IV	Dynamic + Macroscopic pictorial	15	2C-(3Ma-3Su-3Sy)E-4R		2	7 (11.86)	
			14	2C-(3Ma-3Su-3Sy)E-3R		1		
			13	2C-(3Ma-3Su-3Sy)E-2R		1		
			10	2C-(3Ma-3Su)E-2R		1		
			9	2C-(1Ma-3Su-2Sy)E-1R		1		
				2C-(2Ma-3Su)E-2R		1		
	V	Notational pictorial	15	2C-(3Ma-3Su-3Sy)E-4R	2		5 (8.47)	
			14	2C-(3Ma-3Su-3Sy)E-3R	1			
			13	2C-(2Ma-2Su-3Sy)E-4R	1			
			12	2C-(3Ma-2Su-3Sy)E-2R	1			
Inappropriate	n/a (1)	Inappropriate pictures but good in writing	12	2C-(2Ma-3Su-3Sy)E-2R		1	3 (5.08)	9 (15.25)
			10	2C-(1Ma-2Su-3Sy)E-2R		2		
	n/a (2)	Inappropriate evidence	12	2C-(3Ma-1Su-3Sy)E-3R	2		6 (10.17)	
			11	2C-(2Ma-1Su-3Sy)E-3R	1			
			10	2C-(1Ma-1Su-3Sy)E-3R	1			
			8	2C-(1Ma-1Su-2Sy)E-2R	1			
			4	2C-(1Ma-1Su)E		1		
Total					30	29	59	59

n/a = Not Available, F=Frequencies of Students, Sc.1=School 1, Sc.2=School 2

In figure 7, we found that a group of students who made sub-microscopic evidence using pictorial mode (mean = 12.54, SD = 1.92) got higher average mean scores than those who made inappropriate pictorial mode (mean = 9.89, SD = 2.57). This comparison indicates that representing phenomena by drawing pictures supports students' ability to construct a scientific explanation of the galvanic cell content. This finding accords with the studies of Areljung, Skoog, and Sundberg (2022), Tyler, Prain, and Hubberm (2018), and Ainsworth, Prain, and Tytler (2011), that proposed the advantages of drawing pictures to represent scientific concepts.

In addition, analyzing a major group of 50 students who made pictorial mode, we found five types of sub-microscopic representation arranged from highest to lowest percentages.

I. Chemical Equation pictorial: 15 students (25.42%) with 5 categories.
II. Dynamic pictorial: 15 students (25.42%) with 9 categories.
III. Macroscopic pictorial: 8 students (13.56%) with 5 categories.
IV. Dynamic + Macroscopic pictorial: 7 students (11.86%) with 6 categories.
V. Notational pictorial: 5 students (8.47%) with 4 categories.

The details and samples of each type are illustrated in table 6.

Table 6 Samples of five types of pictorial sub-microscopic evidence

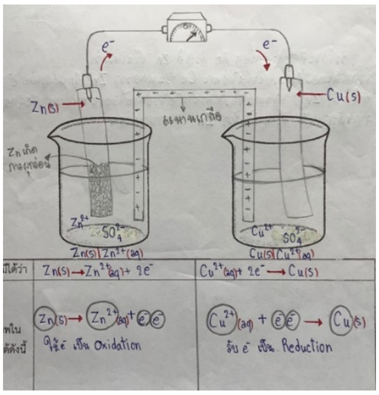
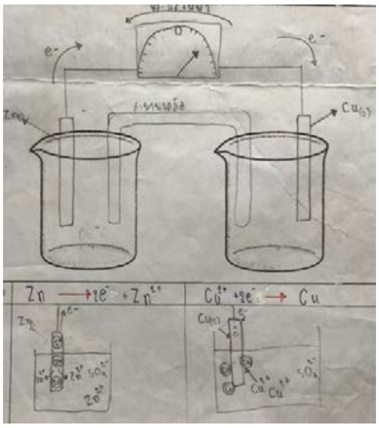
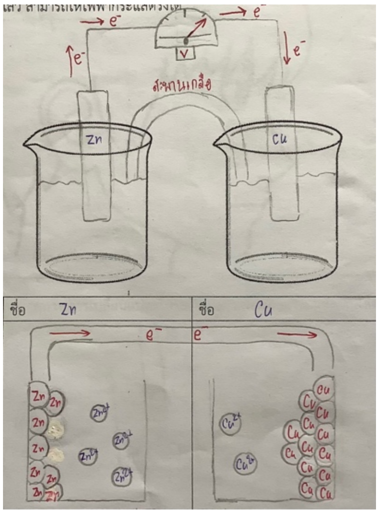
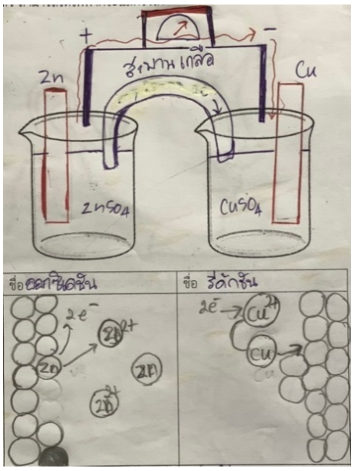
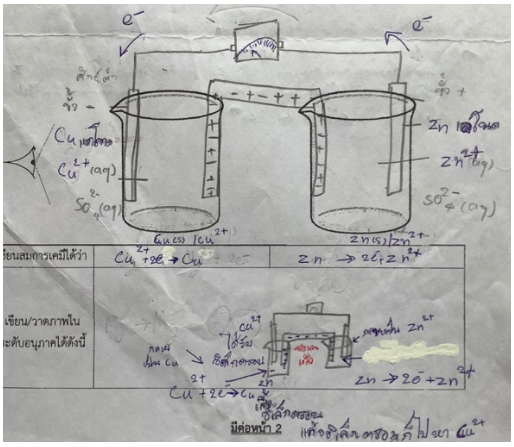
Types of pictorial sub-microscopic evidence	**Descriptions**
I. Chemical Equation pictorial 	**Sc1No23**: 2C-(3Ma-3Su-3Sy)E-3R=14 Students expressed sub-microscopic evidence by drawing circles to represent atoms and ions as a chemical equation of two reduction and oxidation reactions. That chemical equation is one of symbolic form, i.e., students represented sub-microscopic ideas by symbolic.
II. Dynamic pictorial 	**Sc1No33**: 2C-(3Ma-3Su-3Sy)E-4R=15 Students made sub-microscopic evidence by drawing arrows to show the flow of losing and gaining electrons of the anode and cathode, respectively. In addition, some circular symbols of atoms and ions also were shown to clarify their ideas.

Table 6 (Cont.) Samples of five types of pictorial sub-microscopic evidence

Types of pictorial sub-microscopic evidence	Descriptions
III. Macroscopic pictorial 	**Sc2No01**: 2C-(3Ma-3Su-3Sy)E-2R=13 Students of this group made sub-microscopic evidence by making atomic and ionic pictures as many circles. Those pictures were proposed based on the thickening and the corrosion of metals which were the macroscopic phenomena they can observe in classroom activities.
IV. Dynamic + Macroscopic pictorial 	**Sc2No03**: 2C-(3Ma-3Su-3Sy)E-4R=15 Students illustrated their sub-microscopic ideas by making arrows to show the flow of losing and gaining electrons on oxidation and reduction reactions: (type II dynamic), together with the thickening and the corrosion of metals (type III macroscopic phenomena).
V. Notational pictorial 	**Sc1No06**: 2C-(3Ma-3Su-3Sy)E-4R=15 Students of this group used a series of written symbols and arrows to show their ideas of sub-microscopic representation. Some sentences or phrases were written to support their concepts of gaining and losing electrons. In addition, two chemical equations of oxidation and reduction also were illustrated.

These findings of the five different types of students' making sub-microscopic evidence can emphasize the importance of several kinds of learning styles. Personal methods to make the meanings of natural phenomena are formed from prior knowledge and experiences. If science educators and teachers understand the student's individual differences and the contexts of each school, it would be effective in learning science (Tobin & Tippins, 1993). Therefore, the stages of this instructional strategy have also been adjusted to fit classrooms' occurrences as phenomenological-based designs.

Adjusting the stages of the instructional strategy

In stage 1 of the instructional strategy, students must experiment without fixed directions. Each student's group could independently design to pair any kinds of 4 metals: aluminum, copper, magnesium, and zinc, to their appropriate electrolytic solutions (we provided more than four kinds). If an electrolytic solution is inappropriate for its metal, the reaction might not happen.

Our critical peer at School 2 seriously reminded us about this independence because two of six groups chose the wrong electrolytic solutions. S/he suggested that the first author needed to clarify the experiment's details more clearly. However, this was our will. We wanted students to learn from their mistakes. This wrong selection affected their experiments not working. However, we supervised them to check their private group's voltmeter: does it work? At the same time, the first author persuaded other groups to share the results of the experiments. Then both groups learned from those friends' experiments (each group had chosen different kinds of metals and electrolytic solutions). So, these two groups could experiment again smoothly, and it worked.

Based on the theoretical frameworks, our persuasion to students to share their ideas should do in stage 3: conducted under the concepts of Vygotsky's internalization process, see table 1. However, the Share Ideas between Group Discussions stage occurred during stage 1: Learn through Macroscopic Phenomena because of the wrong selections of electrolytic solutions.

This classroom occurrence pointed out the overlapping of stage 3 with others. We would argue that sharing ideas can be conducted at any stage because students learn in the same room where each group can see each other. The process of sharing ideas can generally occur; students have already known results from other groups all the time naturally. Thus, the Revised version of the strategy would be proposed together with the Original version; details are in figure 8.

Figure 8 Original and Revised versions of the instructional strategy

In figure 8, stage 3 of the Revised version has been added in every other stage, making this instructional strategy more flexible. Teachers' teachings and students' learnings should be adaptable activities; the contexts are essential. Science educators and teachers can employ any version of the strategies depending on their classroom situations. This adjusting of the instructional strategy accords to some research that changed their pedagogy based on contexts, such as the study of Commons (2007), which changed the teaching methods in several aspects to improve students' learning to read. In addition, Ghosh (2022), Luik and Lepp (2021), and Carroll, Chaparro, Rebensky, Carmody, Mehta, and Pittorie (2021) have adapted and adjusted their teaching strategies for different groups of students during the COVID19 pandemic. Immediately context-based adjusting the strategies during teaching can support students in constructing scientific explanations for electrochemistry.

Conclusions

The purpose of this study is to assist students can construct their explanations of electrochemistry that have been indicated as complicated content. Therefore, the teaching strategy was developed from the philosophical ideas that were warranted through research conduct and had to be in credible publications. The strategy was planned and split into sub-stages to make it easy to implement in classrooms. Also, the educational pieces of stuff (worksheets, whiteboard, model sheets, laboratory equipment) were designed and developed based on theoretical backgrounds in order to support students could reach the scientific phenomena they should understand. They would bring their understanding of those phenomena to construct an explanation based on their academic experiences.

This study has developed a method to measure the students' explanation ability (see table 2). This method was formed based on the well-known theories that came from reviewing the literature. The product from this measurement has been displayed in the categories. Each category consists of five sub-components of the explaining ability. In addition, these categories would have a score that fits students personally; the score can benefit teachers to understand their students more profoundly. Another unique property of this measurement is that although some students got the same score, they may have different components. Teachers can effectively use this data to analyze students' abilities, leading to educational success because explaining natural phenomena is the main aim of learning science.

This study found the importance of using pictorial and written modes as evidence that supports students' explanation ability. In addition, several types of students' expressing sub-microscopic ideas have indicated the students' differences, and several kinds of learning styles should be concerned by chemistry teachers and educators.

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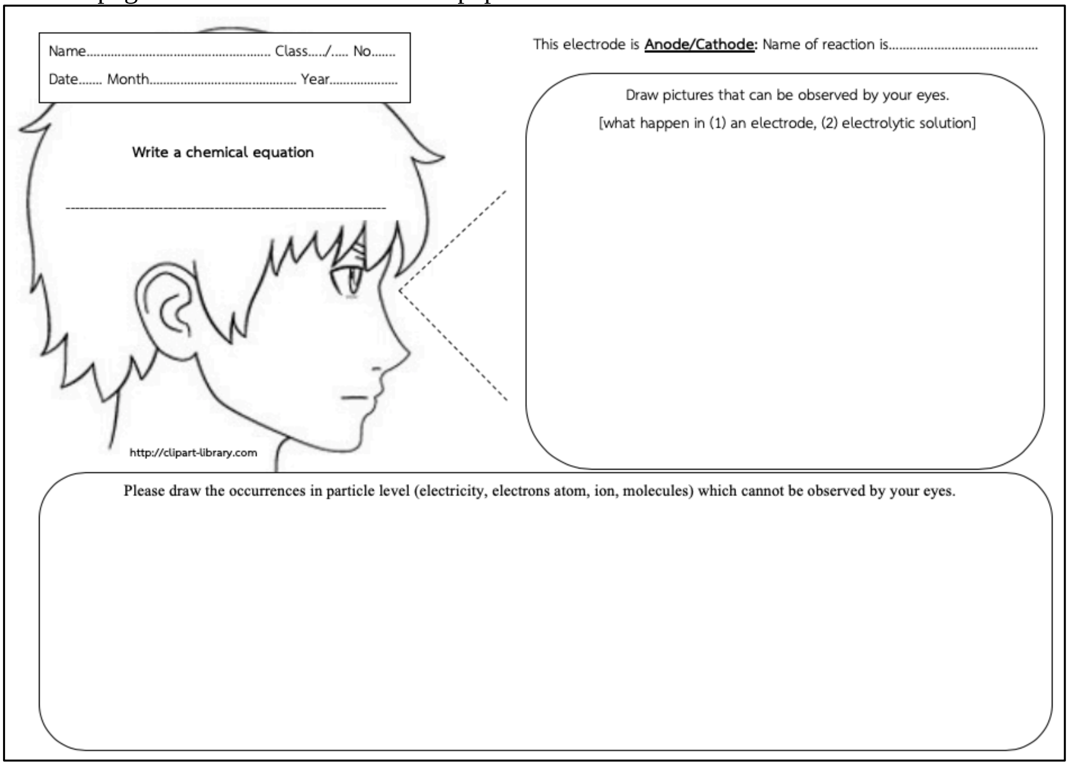
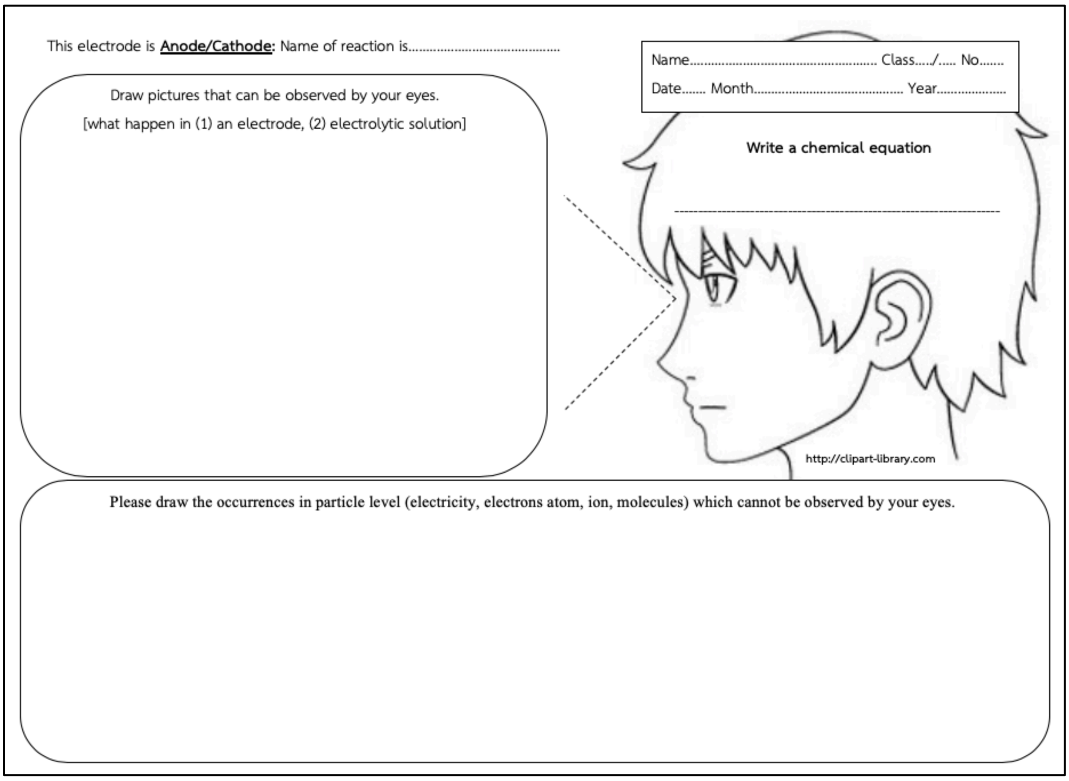
Appendix A

The Writing-Drawing on the Chemical-Electrical Representations (WDCER) Worksheets

The left page: The actual size is A4 size paper.



The right page: The actual size is A4 size paper.



Appendix B

The Worksheet for Supporting the Ability in Constructing Scientific Explanation (SACSE)

Worksheet for supporting the ability in constructing scientific Explanation

(SACSE)

Name.. Class...../..... No......

Date......... Month... Year...............

Please write and draw any things can help you construct an explanation about: if we connect two half-cells $Cu(s)|Cu^{2+}(aq)$ and $Zn(s)|Zn^{2+}(aq)$, can we produce the direct electric current? Please make ✓ into ☐

Answer: ☐ CAN produce ☐ CANNOT Produce

Names of half-reactions		
write/draw evidence in particle level		
Chemical equations		
A balance equation		

Tips & Tricks: your explanation should contain

1) Evidence and Reason that can be observed by eyes
2) Evidence and Reason that cannot be observed by eyes
3) Evidence and Reason in symbolic forms

How can you provide **reasons** to link a conclusion and pieces of evidence? (Why the connecting of two half-cells can produce the direct electric current?) Please explain explicitly.

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Appendix C

Content Specific Rubric Scores for Examining Scientific Explanations: Galvanic cell

Claim

Credit	Level	Answer	Clarification
2	Correct Claim	Can produce the electric current	Students mark ✓ symbol in the blank ☐
1	Alternative Claim	Cannot produce the electric current	Students mark ✓ symbol in the blank ☐
0	No Claim		Not Available

Evidence

Credit	Levels	Criteria		
		Macroscopic evidence	Sub-microscopic evidence	Symbolic evidence
3	Sufficient level of evidence	Provides 1) The corrosion of Zn(s) 2) The thickening of Cu(s) 3) Moving of needle direction of voltmeter (direct to copper metal) by writing and/or drawing	Draw atomic/particle level pictures and/or write as notation that show Zn(s) atoms lost 2 electrons and becoming Zn^{2+}(aq) or Cu^{2+}(aq) gained 2 electrons becoming Cu(s)	Write two chemical equations of 1) An oxidation reaction which losing electrons 2) A reduction reaction which gaining electrons
2	Partial level of evidence	Provides 1 appropriate pieces of evidence	Draw and/or write atom/particle level but incomplete	Write chemical equation of electron transfer but incomplete
1	Alternative level of evidence	Provides only inappropriate macroscopic evidence (or non-chemical principle)	Draw and/or write only inappropriate particle level of evidence (or non-chemical principle)	Write alternative chemical equation of electron transfer (or non-chemical principle)
0	No evidence	Provides nothing	Provides nothing	Provides nothing

Reasoning

Credit	Levels	Criteria	Clarification
4	Excellence	Provides all three chemical representations: macroscopic, sub-microscopic and symbolic evidence link the claim. Includes appropriate and sufficient scientific principles.	Students may only write, or only draw pictures, or both write and draw which can link chemical evidence to claim. Use all three kinds of evidence support the claim. Can refer classroom laboratory findings to their explanation (provide reasons for linking claim and evidence based on electrochemical principle)
3	Good	Uses 2 of three chemical representational evidence support the claim.	Students provide correct evidence but is not sufficient or do not support the claim
2	Developing	Uses 1 of three chemical representational evidence support the claim.	
1	Unacceptable	No overall understanding of explanation. No three chemical representational evidence. Uses alternative evidence support claim.	Students do not provide correct evidence and/or cannot link evidence and claim
0	No reasoning	Students do not write or draw anything	