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Impact of Teachers' Overcoming Experience of Threshold Concepts in Chemistry on Pedagogical Content Knowledge (PCK) Development

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ABSTRACT. As a follow-up study to identify references for threshold concepts in science, 20 high school chemistry teachers were interviewed. Seven concepts were identified as threshold concepts. The data revealed that teachers overcome the thresholds while they are teaching as well as learning during their school years. This explains that the mastery experience of threshold concepts involve not only the process of creating subject matter knowledge of a learner but also the reflection on or preparation for teaching. Hence, the current study proposes that a strong relationship exists between the mastery experience of threshold concepts and the development of teachers' pedagogical content knowledge (PCK). In this regard, findings from this study will provide valuable information to understand the nature of threshold concepts and suggests the value of mastery experience of threshold concepts in terms of PCK development.

Key words: Threshold concepts, Pedagogical content knowledge, Integrative feature

INTRODUCTION

Despite remarkable advances in science and technology, many students have confided that they find scientific concepts difficult, and often think of science as an alien language in which they cannot communicate meaningfully. This led the author of the current study to search for potential threshold concepts in the field of science. According to Meyer and Land,[1] a threshold concept is a portal or gateway that can be reached through "a transformed way of understanding, or interpreting, or viewing something, without which the learner cannot progress." Threshold concepts may be similar to core concepts in each subject area, but they can be more complex due to the nature of transformative, integrated, bounded, irreversible, and troublesome aspects of the concept. In other words, understanding a threshold concept, or overcoming the threshold barrier, requires a learner to have a holistic understanding of the concept and related theories (characterized as "transformative" and "integrated") as unforgettable knowledge (characterized as "irreversible"). Moreover, since threshold concepts are troublesome concepts, they challenge the learner.

Based upon the phenomenographic perspective of defining "a way of thinking," Davies[2] mentions difficulties in pinning down thoughts and the features differentiating them. With respect to the difficulty of research, Davies[3] suggests two different approaches, revealing variations in the learning experiences associated with threshold concepts. First, professionals with expertise and learning experience in the field can develop the list of threshold concepts through common agreement.[4] Alternatively, student responses describing conceptual understanding and learning can be scrutinized by researchers to identify candidate threshold experiences.[5–7] In general, threshold concepts in a specific field provide clues to understand student learning, and can be good references for instructional practice.

In order to build a reference list of threshold concepts in science, high school chemistry teachers and students were studied. For the purposes of this report, only data from teachers will be discussed. Chemistry teachers suggested several potential threshold concepts in high school chemistry, as well as how they perceive that these concepts affect teaching and learning chemistry. Based on the teachers' responses, we explored mastery experiences around these threshold concepts, as well as their influence on teaching. Data show that teachers overcome the thresholds while they are teaching as well as learning during their own schooling. This is the uniqueness of teachers' overcoming experience of threshold concepts. Hence, we consider teachers' mastery experiences with regards to threshold concepts as not only part of the process of building subject matter knowledge (SMK) in learners, but also as important for inducing reflection on or preparation for teaching.[8] This calls to mind "the synthetic or synergistic impact of knowledge-in or knowledge-on action" on pedagogical content knowledge (PCK).[9,10] Accordingly, the current study investigates the strong relationship between mastery (or awareness) experiences of threshold concepts and the development of teachers' PCK. By examining teachers who were beginning to build their content expertise,[11] Shulman and colleagues searched for a way to explain knowledge required for the teaching occupation. To do this, they paid special attention to teachers' transitions from expert students to novice teachers as they gained content knowledge. Their probe initially identified three types of teachers' knowledge: content knowledge (SMK), PCK, and curricular knowledge (contextual knowledge). Among them, Shulman[12] considered PCK a representative knowledge, characterizing the teacher as a professional. Shulman further explained that PCK is developed from the interaction of particular kinds of content knowledge and pedagogical strategies. In later studies, types of teachers' knowledge and sub-categories of PCK were further studied and classified in a variety of ways.[10,13,14] For example, in the introduction of "Examining pedagogical content knowledge," Gess-Newsome[15] defined PCK as an integrated mixture or transformed compound of three constructs: subject-matter knowledge, pedagogical knowledge, and contextual knowledge. However, Grossman[16] classified knowledge into the four different domains of SMK, general pedagogical knowledge, knowledge on the context, and PCK. Although the classification of related knowledge types differed according to researchers' perspectives on prerequisites, domains, or sub-components, many studies have opted for the following definition of the crucial elements of PCK: (1) knowledge of student understanding, (2) knowledge of subject matter, (3) knowledge of instructional strategies, and (4) knowledge of curriculum.[17–21] Starting from an inquiry tracing teachers' knowledge and the transition process in teaching, studies revealed the value of PCK as a useful tool in the design of teacher education programs and as a measure of teacher evaluation.[22–26]

As mentioned previously, several studies including the current study[27,28] have reported that teachers more often have mastery experience while working as teachers than during their own schooling. This made us recall Shulman's earlier inquiry on the transition from expert students to novice teachers. Related to this, the importance of "learning through experience" was clarified at the beginning of the book (chapter one) "Understanding and developing science teachers' pedagogical content knowledge." Studies on PCK have often compared the SMK of experts and teachers, in order to analyze the characteristics of PCK. In the process, several studies highlighted the value of SMK for PCK.[14,29–31] Conversely, Johnson and Ahtee[32] doubted the consequential relationship between the two. They instead argued about the quality, not the quantity of teachers' SMK. Likewise, considerable differences between PCK and related SMK were explored in Onno De Jong *et al.*'s study.[33] However, there were no specific details about the quality and difference of the two, which indicates that despite frequently raised questions, there are not many studies investigating direct relationships between the two. In this respect, the current study investigates how PCK and SMK are related. Teachers' experiences of overcoming thresholds in learning and teaching are expected to be clues that provide further clarity about the quality of SMK and PCK, and how they are different from each other. To that end, we first investigated the common ground of PCK and threshold concepts (TC); the impacts of experiences of overcoming threshold concepts (TCs) on teaching were then examined in detail. Through interviews with high school chemistry teachers, this study identified threshold concepts in chemistry, and their educational implications, especially their usefulness and applicability for designing curriculum and instruction. From our analysis, the importance of teachers' experiences of overcoming threshold concepts in their subject areas will be discussed in light of the development of PCK in teacher professionals.

METHOD

Data setting and participants

In order to identify threshold concepts in chemistry, data were collected from teachers who had majored in chemistry or chemistry education. They had completed the required chemistry and education courses that qualified them for government-authorized teacher certificates. Twenty chemistry teachers from several high schools located in various areas of South Korea participated in this study. First, the teachers responded to a questionnaire that aimed at identifying threshold concepts and explaining their learning and teaching experiences related to the concepts. Second, they were invited to a follow-up interview designed to elicit details about their responses on the questionnaire. The interviewees differed in their amount of teaching experience, location, education, and gender. Nine male and eleven female teachers participated in the interview. Seven teachers held a master's degree in science education. Six teachers held a master's degree in chemistry, among whom two had a doctorate in the field. Nine teachers had worked in the profession for ten years or less, and the rest had more than ten years of experience.

Instrument and data analysis

The teachers were asked to write responses on an open-ended questionnaire; they were then interviewed to add

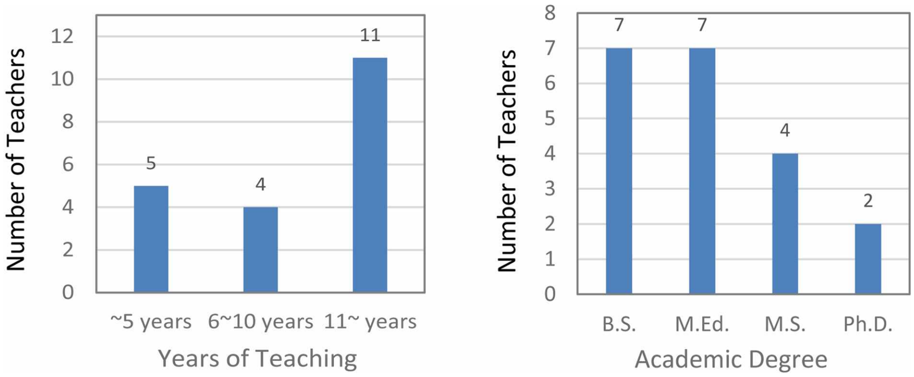

***Figure* 1.** Distribution of teachers by experience and education.

details to each response. They suggested potential threshold concepts in high school level chemistry on the questionnaire. The questionnaire was administered around the third week of the fall semester. During the following months (October through December), interviews were conducted to verify the teachers' suggestions as threshold concepts. The 11-item questionnaire was e-mailed to all teachers. The first four items (1~4) were prepared to gather background information categorizing teachers by gender, school location, education, and years of teaching experience. The rest of the questionnaire items asked about the teachers' thoughts and experiences in terms of threshold concepts (see Appendix A). Considering the differences between "important," "difficult," and "threshold" concepts as suggested by Park & Light[34], items 5, 6, 7, and 8 asked teachers to describe their thoughts and experiences about the first two (important and difficult) concepts in chemistry. On item 9, the teachers were asked to identify concepts considered "threshold" in learning chemistry, and item 10 then asked for their reflection on the experience of overcoming threshold concepts. As well as revealing potential threshold concepts in chemistry, the analyses of items 9 and 10 revealed how teachers understood the scientific meaning of each concept, which itself may be a source of difficulty inherent in learning the concepts. Conversely, item 11 was prepared to examine the relationship between understanding threshold concepts and teaching.

11. When you are teaching threshold concepts, if you have the experience of overcoming the threshold barrier, how do you teach? Is there any difference with teaching other concepts?

The follow-up interviews took approximately 40 to 60 minutes to elicit details about the teachers' responses on the questionnaire. They also provided reasonable evidence supporting selected threshold concepts. Key features of threshold concepts were cited to describe teachers' criteria for the selection. At the end, the interview included one more item asking about the value of applying threshold concepts to the development of instruction and curriculum materials (see Appendix B). All responses were categorized qualitatively, and the frequencies of identified categories were measured. Data analysis of findings from the questionnaire responses was used to develop initial categories for each item, and the initial categories were further elaborated along with the interview data analysis. The current study is primarily based on the analysis of the interview responses. In interviews in particular, since teachers provided multiple responses to a question and the numbers of responses varied, the frequency of each category is not included in this paper; responses were instead classified by descriptive analysis. For the analysis of teachers' written or verbal responses, three researchers with a background in science and education (two Masters of Science, one PhD in science education with Chemistry master's) participated. For each item, researchers individually analyzed the teachers' responses and constructed a list of categories characterizing them. Through in-depth discussion, common codes appropriately representing all teachers' responses were developed. In order to measure reliability among raters, the three researchers randomly selected and separately coded five teachers' responses (written responses to the questionnaire – interview transcripts). Codes from the three raters agreed with 86.4 percent correspondence. Two of the three researchers assessed all 20 teachers' responses using the common codes and achieved an agreement of 95.3 percent. The third researcher was consulted to resolve conflicting ratings.

RESEARCH FINDINGS

Threshold concepts in chemistry

Based on the learning and teaching experiences reported

***Table* 1.** Threshold and related concepts identified by high school chemistry teachers

Threshold Concept	Linked Concepts	
	Concepts of Lower Complexity	Concepts of Higher Complexity
Mole	Atom, Avogadro's number, formula weight	Concentration (molarity, molality), molar ratio, acid-base neutralization, pH value, chemical stoichiometry, ideal gas law related problem solving, calculation, colligative properties, analytic chemistry calculation problem solving
Ideal Gas Law	Boyle's law, Charles's law, Avogadro's law, mole, gas, molecular movement, gas laws	Van't Hoff equation, molar ratio and density of gases
Periodic Table	Atom, atomic theories, structure of an atom, electron configuration,	Periodic properties of atoms (atomic ratio, ionization energy, electron affinity, electro negativity), structure of a molecule, chemical bonding, carbon compounds
Structure of an Atom, Electron Configuration	Atom, element, periodic table	Periodic properties of atoms, chemical bonds, chemical reaction, orbital, quantum chemistry
Orbital	Particle in a box	Atomic/molecular orbital theory, quantum chemistry, probability, mathematics, electron configuration, ion, chemical reaction, molecular force
Chemical Bond	Periodic table, properties of atoms, metals/non-metals/metalloids, transition	Structure of molecules, molecular force, carbon compound, chemical bond
Chemical Equilibrium	Chemical reaction, chemical kinetics	Equilibrium constant, Le Chatelier's principle, various chemical reaction

by 20 high school chemistry teachers, the current study identified seven threshold concepts in high school level chemistry, shown in *Table* 1 above. Related or linked concepts to the threshold concepts are also listed in the table. When the teachers were asked about the integrated or transformative features of selected concepts, they addressed the related concepts to describe conceptual changes in their learning experience. Teachers listed these concepts after considering curriculum guides, textbooks, and their own lessons. Some were concepts that needed to be learned in advance and others were learned at higher levels (grades). Because the teachers were able to see all of them as one or realize the hidden thread connecting them, the critical ones were referred to as threshold concepts. This well describes the integrated feature of a threshold concept, which, as it is a crucial concept, connects other concepts. Many teachers in this study first picked the "periodic table" as a threshold concept in chemistry, followed by "orbitals" and "structure of an atom." In particular, as integrated concepts in lower or higher complexity links, the four concepts: periodic table, orbitals, structure of an atom, and chemical bonds, are intensely associated with each other.

Some teachers did not find any concepts at the high school chemistry level to be particularly difficult or troublesome. However, although it was not that difficult for them to pass school examinations and to gain qualifications as chemistry teachers, these teachers admitted that they did have "a-ha" experiences when they learned or taught certain concepts in high school or elsewhere. Moreover, there still remained areas or barriers in which some teachers had not experienced transformations in understanding. For example, the concepts of electricity, entropy, and the physical/scientific meaning of mathematical representation in quantum chemistry are on teachers' list of difficult concepts. This needs to be further studied by comparing teachers' understanding with responses from expert scientists who have mastered and made the corresponding conceptual transformations. Then we may have more threshold concepts. Although "atoms" and "chemical bonds" were cited most as important concepts, many teachers stated that the scholastic ability test for college admissions is another key factor determining the importance of concepts. Therefore, their responses were mainly related to how to solve the problems. This reveals how teacher responses in the three categories are different. In this regard, the prior study[34] can be referenced.

Types of experience

The identification of threshold concepts is based upon teachers' mastery experiences and by conceptual transformations. Described as an "a-ha!" moment by several teachers, the experience of overcoming the troublesomeness of threshold concepts is unique and is accompanied by a transformed way of thinking. Interview data analysis shows that chemistry teachers achieved such moments of awareness in various ways. *Table* 2 lists how or when the chem-

Table 2. Moments of awareness and ways of achieving them

Types of Experience	Ways of Overcoming Thresholds
Conceptual Understanding	· Learning higher level concepts · Iterative memorization/reading · Examining references · Solving problems · Questions and answers with teachers or friends
Contextual Understanding	· Understanding contextual meaning of a concept (related concepts, relationship, origin, flow, etc.) · Understanding the relationship between concept/theory and formula explaining it · Understanding the meaning of models, diagrams, tables · Understanding the relationship between concept/theory and experiment/natural phenomena
Teaching Related	· Reflection on teaching · Lesson plan and review with the refection on student understanding · Student assessment · Questions and answers with students
Professional/ Teacher Development Program	· Paper/thesis writing · Experiment as a scientist · Active discussion with peers, experts, experienced teachers

istry teachers had their moments of awareness.

Learning in itself is development and progress. Learners build knowledge through the process of learning; however, conceptual understanding of threshold concepts goes beyond the cumulative build-up of knowledge. Thus, in the case of mastering threshold concepts, the process of learning provides opportunity for learners to form conceptual understandings and then experience transformations in their thinking. Teachers in this study understood some concepts immediately; others they found initially difficult to comprehend, but gradually, they deviated from "liminal status"[35] to comprehending them conceptually. As summarized in *Table* 2, some teachers comprehended a threshold concept while learning higher-level concepts in the subject, examining reference materials, or solving related problems. Other teachers attained conceptual understanding and transformation through the iterative processes of memorization, reading, and frequent consultation with their colleagues. Teachers also cited participation in higher education or degree programs as opportunities to enrich these experiences of overcoming knowledge blocks. Although the meaning of comprehension can be subjective, most teachers had mastered concepts such as "mole and periodic table" in high school chemistry class. Depending on the concepts, the teachers' experiences of their awareness varied. Five teachers said that they had learned the concepts meaningfully and made conceptual transformations during their college studies. In addition, two addressed the importance of inquiry experiences in the laboratory and thesis processes, including writing, which usually happened in graduate school. This is well explained in the excerpt below:

Teacher KJ*: I was O.K. I mean I was a high achieving student in high school. I was highly ranked in my grade as well as in science. My knowledge of science was good enough to pass all the tests given by the school and even good enough for the college entrance exam. It didn't matter how I completely understood the concept or not; I think I had a fair understanding for high school level science. However, when I look over my past years, I think my understanding in high school was pretty superficial. For example, in regard to the concept of orbital, I understood the meaning of probability and its mathematical representation from college science courses. From studies related to the coursework, I linked prior knowledge that existed as fragments to a whole, and I think that gave me another transformative moment compared to my previous understanding in high school, together with integrating parts.*

This opportunity for higher education can be extended to professional development programs such as workshops, seminars, conferences, and teachers' social activities. Third, teachers mentioned that they had "a-ha" moments while teaching or preparing lessons. Teaching entails student reactions. In this regard, the teachers in this study raised one similar question from their earlier teaching experiences: "Why don't my students understand this concept?" Alternatively, "Why is this concept difficult for them?" From that moment on, the teachers sought ways to help students understand, or to reduce the difficulties of learning science. In order to prepare lessons, teachers had to re-structure their knowledge into an easily achievable form appropriate for students' ability levels. Through the processes of reflection and re-construction, many teachers in this study experienced a transformative understanding of threshold concepts.

Teacher IY*: While I was preparing lessons and thinking of answers to student questions, in particular, about how to teach, how to deliver, and which way may be the best, I was able to comprehend the meaning of formulas and concepts that were simply memorized and used for problem solving previously. I then seemed to be enlightened by this holistic understanding. I think that "to know" and "to be aware of" are different. I think I became aware of the concepts through teaching or preparing for teaching. That was the "a-ha" moment that I vividly remember.*

The importance of contextual understanding was also presented as a critical component of mastering the threshold concepts. Seven chemistry teachers mentioned that understanding of the threshold concepts in a transformative way was accompanied or achieved by understanding the flow, contextual structure, or relatedness of concepts in the subject. The integrated nature of threshold concepts was valued by recognizing them not only as single concepts but also concepts integrating contextual information and related concepts. According to the teachers, they experienced "a-ha" moments when they figured out the relationships between related concepts, models and entities, parts and the whole, experimental data and theoretical background, real-life experiences and theoretical descriptions, mathematical representations and scientific meanings, and formulas and explanations. One teacher, LJ, explained that drawing a "big picture" provides insight, mapping the integrated aspect of science as well as achieving conceptual understanding. Furthermore, two teachers (LJ & KJ) explained being able to see the link or connectivity of concepts in chemistry itself as the threshold in learning science.

Influence of overcoming the difficulty of threshold concepts

The experiences of overcoming threshold concepts helped chemistry teachers make changes in a number of ways. *Table* 3 summarizes teachers' responses. As for *Table* 2, *Table* 3 lists the categories containing the most responses, rather than indicating the frequency of each response. First, because understanding threshold concepts is transformative, integrated, and irreversible in nature, teachers were able to understand better, think systematically, and thus, internalize the concepts as knowledge that would be hard to forget. Second, the experience of overcoming threshold barriers improved their efficacy as teachers. The mastery experience of understanding threshold concepts helped teachers to abate their fears of teaching chemistry and to gain confidence in their abilities to make students learn. Third, teachers admitted to having attitude changes towards science through these experiences of awareness. Specifically, they developed intellectual curiosity for chemistry, interest in chemistry, and favorable attitude towards chemists. Consequently, these positive changes motivated the teachers to major in chemistry-related disciplines and even to build their careers as chemistry teachers. By loving chemistry, they decreased their anxiety towards it and improved their self-esteem for learning chemistry and science in general. Fourth, the teachers made significant changes in their methods of teaching threshold concepts. The experiences of awareness affected teachers' teaching as well as their learning. This pedagogical change is discussed in more detail below.

***Table* 3.** The influence of experiences of mastering threshold concepts on teachers

Change	Detail
Develop Attitude Toward Science	· Develop favorable attitude toward science and scientist · Develop interests in science and science related activities · Develop interest in majoring in science and pursuing a career in science related work (including teaching science) · Decrease the anxiety toward science or learning science · Develop confidence and self-esteem for science · Develop scientific attitude
Increase Conceptual Understanding	· Improve understanding, awareness · Improve school grades/performance · Improve problem solving · Do not forget and no need to memorize · Develop synthetic prediction
Develop Systematic Thinking	· Develop insight (understand flow, relationships etc.) · Develop different views
Develop Teacher Efficacy	· Decrease the anxiety toward teaching science · Develop confidence for teaching science
Experience Pedagogical Change	· Develop teacher efficacy · Develop instructional strategies · Improve understanding of students, student learning, needs, etc. · Seek advice for teaching science

Pedagogical change as a result of understanding threshold concepts

As pointed out previously, understanding threshold concepts and the experience of this awareness helped the teachers in this study to develop efficacy and confidence for teaching the concepts. However, their confidence was not limited to the threshold concepts. Due to the integrated characteristics of threshold concepts, the teachers stated that they had the confidence to explain threshold concepts and its contextual knowledge. With this preparedness, several teachers admitted that they found it easier to explain the concepts. For example, teacher JK replied as follows.

After understanding this, after experiencing the "a-ha" moment, I think I don't have fear to teach the concept and related theories. To put it simply, I think I don't even need to prepare a lesson plan particularly for the concept. I mean, because I know it well, like I'm saturated enough with the concept, I can answer all student questions related to it. Depending on the students in my class and their level of understanding, I can easily adjust my lessons; in other words, I can explain it simply, or I can teach it in more detail.

The excerpt reveals a crucial effect of embodied subject matter knowledge on pedagogical change or development. Relating to the embodiment of the threshold concept, data show various changes in teachers' pedagogy.

First, teachers who had the mastery experience of threshold concepts tried to re-design the science curriculum structured by the Korean National Science Education Standards. Because of the importance of the annual college entrance exam conducted by the Korean government, most high school science curricula follow the National Science Standards. For this reason, it is not easy to change the science curriculum based on national standards (scope of contents and orders), particularly in the secondary level public school system. Nevertheless, the teachers in this study described that they had made slight changes by regulating the depth and order of some threshold concepts in the existing school science curriculum.

The periodic table is an example. It was supposed to be taught in a sub-chapter "Metal and property of metals" of the introductory level high school chemistry (11^{th} grade, Chemistry I). Lessons about the structure of an atom and atomic theories were covered in 12^{th} grade Chemistry II. To reduce the gap or to enable the students to understand better, some teachers made curricular adjustments. For the topic "periodic table," some teachers gave a brief introduction of atomic structure before teaching the property of metals, and others taught the periodic table to 12^{th} grade students after completing the structure of an atom chapter.

Second, many teachers adopted various instructional aids such as models, video clips, and visual/audial/tactile materials. In general, students have difficulty understanding abstract concepts in chemistry. Most of the threshold concepts identified in this study, particularly orbitals, equilibrium, bonds, electricity, etc., fall into the category of abstract. Many teachers who participated in the interviews expressed concern about the abstract nature of these concepts and their students' related learning difficulties. Although teachers did not describe specific examples for certain concepts, they believed in the positive effect of these instructional materials on student understanding.

Third, based on the same reason for which they used instructional aids, teachers employed a variety of teaching methods. In order to embody and promote understanding of the abstract concepts, they made frequent use of analogies, metaphors, comparisons, and examples. In such cases, some teachers incorporated their own experiences or familiar real-world phenomena/products into the various methods. Because they had experienced "a-ha" moments and conceptual transformations, they tended to emphasize lessons including threshold concepts compared to other topics. Furthermore, teachers developed various questions designed to reveal student understanding and lead students to think or reflect for themselves. Through this thoughtful process, students could identify differences between their understanding and the textbook contents. As this metacognitive thinking helped teachers to overcome conceptual barriers, teachers guided students to see or meet the difficulty of the threshold concepts and encouraged them to overcome these thresholds.

Fourth, teachers' own experiences helped them to better understand student learning difficulties, predict the obstacles interfering with student learning, and plan ahead to fix these gaps or to put stepping stones between student knowledge and the science curriculum goals. Their own student-level understandings again affected their teaching and interaction with students. Teacher LJ admitted that, by looking back on his own experience, he could easily spot alternative conceptions held by students. In PS's case, students were encouraged to participate in science lessons actively and were pushed to ponder methods and solutions to solve problems for themselves. Through this process, the teachers could communicate with students more often and build meaningful rapports with them. Like PS, SH asked students to seek various approaches other than those in the textbooks to understand the concepts. In order to stimulate student learning and increase student confidence in science learning, LH initially provided questions that were simple and easy enough for most of the students to solve, and then she gradually raised the level of her lessons.

Fifth, as teachers experienced "a-ha" moments by understanding links between concepts, theory and experiments, formulas and scientific phenomena, theory and real-life experiences, and concepts and contextual information, they directed students to see the systematic structure of knowledge in each subject. In this vein, instruction was designed to reveal relatedness, connectivity, and the developmental flow of concepts in chapters or subjects. For an example of using formulas, SH usually used a science formula as a tool for encouraging student confidence through solving problems or a tool for summarizing complex description of phenomena in a simplified form.

When I was studying science in high school, I had a tip-using scientific formulas as a tool to summarize theories. I think the formula is a simplified version of a theory. Therefore, it usually helped me to see lots of information such as *potential variables and their relationships, etc. Moreover, I can predict controlling factors of a phenomena or results by changing conditions of variables. For example, the ideal gas law can be written as PV = nRT. Instead of memorizing all theories (Boyle's law, Charles's law, Gay-Lussak's Law, and Avogadro's principle) separately, I can tell all of them with the one formula. By describing scientific phenomena as a formula and extracting related theories from a simplified formula, the two processes helped me a lot to learn science, and I wanted to teach this approach to my students, especially for the threshold concepts such as ideal gas law and periodic tables. In addition, understanding the scientific meaning of formulas helps students to solve problems better, and this can encourage them in learning science.*

To this end, concept maps and flow charts were pointed out as the most frequently used methods in their teaching.

Sixth, expected struggles of students while learning threshold concepts led the teachers to be acquainted with each other. Although teachers had mastered the threshold concepts, such concepts are usually difficult to teach as well as to learn. To improve student understanding, the teachers often asked for advice from other teachers and discussed instructional methods that would best fit their students. By sharing various experiences and instructional methods, the teachers had opportunities for indirect experience and could widen the repertoire of approaches they could take in their science classes.

CONCLUSION AND DISCUSSION

A useful tool for understanding the meaning and nature of threshold concepts in science

Concepts in this study (*Table* 1) were identified by the features of threshold concepts. Although they were selected based on the personal experience of teachers, the defining features of threshold concepts, such as transformative, integrated, bounded, irreversible, and troublesome, became criteria limiting the diversity of the proposed concepts. In line with the given five criteria, the 20 experienced chemistry teachers selected seven concepts as threshold concepts in high school chemistry. In fact, the concepts of atomic structure, orbital, periodic table, and chemical bonds are conceptually inter-related. Considering this, the number of threshold concepts is not as diverse as the number of teachers and their experiences. This suggests that the criteria above are not only a good reference for describing the nature of concepts but also a good tool for objectifying the subjective experience. As explained, a threshold concept is not necessarily a key concept in the subject. However, some threshold concepts such as atomic structure and periodic table are fundamental concepts in the field of chemistry and have a historical significance in science because of their transformative and integrated nature. In this regard, features of an identified concept provide information describing its scientific meaning and distinctive nature in science. This demonstrates the potential value of threshold concepts for science education.

In regard to significant features, the data from this study first reveal the importance of the integrated nature of each concept in chemistry. When many teachers understood the links between concepts at different levels, concepts and contexts, parts and wholes, theories and experiments, formulas and conceptual meanings, problem solving and theories, phenomena and concepts, models and concepts, etc., they had "a-ha" moments; that is, they experienced irreversible transformations, or "awarenesses," by understanding the interrelated structure of these concepts as a whole or system. This is considered higher order thinking in several studies.[36–38] In particular, this holistic and systematic approach helped the teachers to form rational understandings and make scientific predictions about the concept and related phenomena. Therefore, in the development of chemistry curriculum and instruction, encouraging students to perceive the integrated structure of concepts should be taken into account. Second, because the data from this study are provided by teachers, some threshold concepts might be difficult at student levels of understanding. Nonetheless, considering that the teachers' awarenesses were obtained through learning science as students and teaching science to students, the difficulty of each concept allows us to predict the learning difficulties faced by students.[5] The various methods the teachers used to overcome thresholds (for themselves or their students) and their mastery experiences are good resources for them or teachers in general, to prepare lessons on related concepts.

The influence of teachers' experiences of overcoming threshold concepts on the development of PCK

With respect to overcoming thresholds, many teachers (10 out of 20) cited relevant experience in teaching: that is, while preparing for classroom instruction or through/after interactions with students in class, teachers were able to overcome their own difficulties in understanding threshold concepts. Although it may be complicated to map the exact mechanism linking the experience of overcoming threshold concepts and PCK development, what is clear from this study is that there is a relationship between the two.

As suggested in Park and Oliver's study,[10] PCK development is closely associated with the understanding and reflection of teachers within a given context. Through the hexagonal model of PCK for science teaching, they listed six components of PCK: teacher efficacy, orientation to teaching science, knowledge of assessment of science learning, knowledge of instructional strategies for teaching science, knowledge of science curriculum, and knowledge of students' understanding in science. In general, teachers' responses about teaching threshold concepts showed similar patterns to those found in this prior study in terms of PCK development. However, some components were particularly noticeable due to the "a-ha" experience of threshold concepts. *Fig.* 2 below explains how the mastery experience affected knowledge development (both SMK and PCK). To better explain teachers' responses, this study grouped them into three knowledge domains-cognitive, affective, and social domains of knowledge.

As can be seen in *Fig.* 2a, subject matter knowledge obtained through the mastery experience includes factors required to develop PCK as well. Related to this, *Fig.* 2 shows that there are some overlaps between the two experiences (teachers' mastery experience through teaching vs. learning). This reveals similarities and differences between expert learners' SMK and experienced teachers' PCK well. *Fig.* 2b shows that teachers gain knowledge about students (their understanding, difficulty in learning science, etc.) and instructional strategies after teaching experiences. Teachers' knowledge in the cognitive domain is more comprehensive compared to that of expert learners. Details about these differences will be further discussed in a follow-up paper, by comparing interviews from expert scientists and science

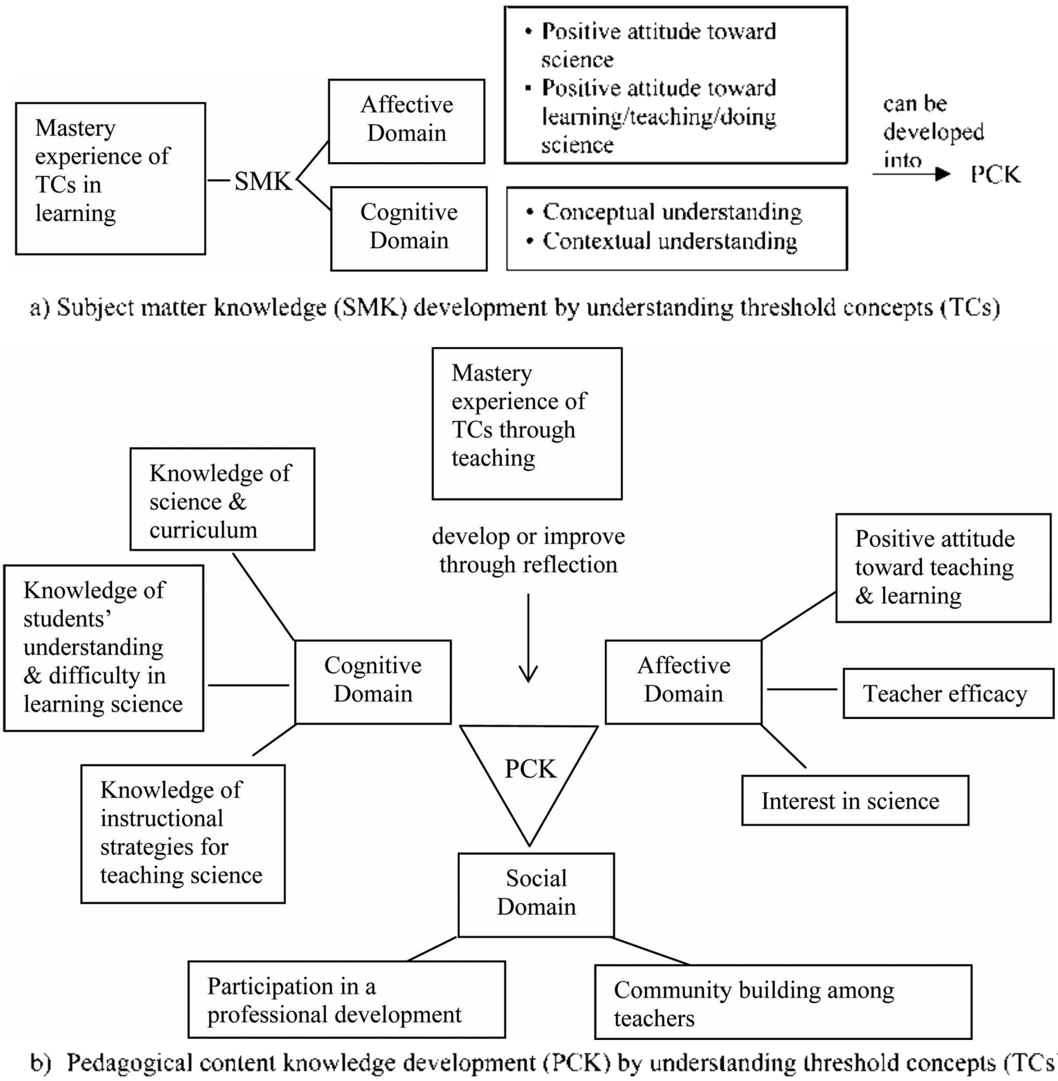

***Figure* 2.** The influence of understanding threshold concepts on the knowledge development of teachers.

teachers (in progress). As stated in teachers' responses, teachers' awareness ("a-ha" experiences) through teaching or interactions with students had great influences on PCK development. Furthermore, affective domains of knowledge seem to be strengthened while teaching. Perhaps the "a-ha" experience itself improved teachers' attitudes to the subject matter considerably (positive attitude toward science teaching/learning, teacher efficacy, interest in science), while advances in the cognitive domain inspired teachers to reflect thoughtfully on their teaching, content, and their own students. Although some were easy concepts for teachers to learn as expert students, the mastery experience helped teachers to better understand the nature and scientific meaning of threshold concepts in science. This suggests that they were aware of the transformative and integrated aspect (at least) of the threshold concepts. In interviews, many teachers discussed the importance of understanding the integrated feature of concepts, which in turn, worked as a meaningful guide to better understanding student learning, and to reflecting on their teaching. In addition to affecting the cognitive domain, "a-ha" experiences improved other domains. This synergistic link between the cognitive and affective domains seems to accompany teachers' knowledge development in the social domain. The term "reflection in- or on-action"[39] well explains what the teachers who participated in this study did after/through their awareness of threshold concepts for/with their students.

In this regard, we can review many studies that questioned the role or effectiveness of subject matter knowledge to teaching science.[40–44] As a distinct knowledge base or a part of PCK, subject matter knowledge (chemistry content knowledge in this study) is an important component for teaching, which was well stated by explaining PCK as subject-, content- or domain-specific knowledge type in Geddis' study.[45] However, having a degree in a subject area does not guarantee that teachers are professional in their teaching.[46–49] In particular, the inefficiency of superficial learning or rote-memorization for problem solving has been pointed out in many learning studies. It reminds us of the importance of overcoming thresholds or gaining awareness of subject matter rather than simply accumulating knowledge through the degree program. In this sense, "a-ha" experiences are potential keys by which students learn science meaningfully; these experiences may therefore work as good instructional tips for teachers. Again, the features of threshold experiences can be good criteria for evaluate teachers' knowledge (SMK and PCK). In addition, teaching experiences themselves were factors stimulating teachers to overcome thresholds in their subjects. Findings from this study have implications for teacher education programs. For both pre-service teachers and in-service teachers, this study, including the research in progress (1. targeting students and expert scientists, 2. different subjects in science), will provide valuable information for understand the troublesome nature of threshold concepts, student learning, and teaching/learning tips from teachers and experts.

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REFERENCES

1. Meyer, J.; Land, R. (2003). Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practicing within the disciplines. ETL project Occasional Report. University of Edinburgh. http://www.etl.tla.ed.ac.uk/docs/ETLreport4.pdf.
2. Davies, P. Threshold concepts: how can we recognize them? In *Overcoming barriers to student understanding: Threshold concepts and troublesome knowledge*; Meyer, J. H. F., Land, R. Eds.; Routledge, 2006; p 70.
3. Davies, P. Threshold concepts: how can we recognize them? Proceedings presented at the EARLI Conference. http://web.staffs.ac.uk/schools/business/iepr/etc/WorkingPapers/etcworkingpaper1.pdf, 2003.
4. EcEdWeb Economic concepts students should know, available at http://ecedweb.unomaha.edu/home.cfm (accessed 19, February, 2013), 2003.
5. Park, E.; Light, G. *International Journal of Science Education* **2009**, *31*, 233.
6. Cheek, K. A. Why is geologic time troublesome knowledge? In *Threshold concepts and transformational Learning*, Meyer, J. H. F.; Land, R.; Baillie, C. Eds.; Sense Publishers, The Netherlands, 2010; p 117.
7. McCartney, R.; Eckerdal, A.; Moström, J. E.; Sanders, K.; Thomas, L.; Zander, C. Computing students learning computing informally. In *Proceedings of the 10th Koli Calling International Conference on Computing Education Research*, 2010; p 43. ACM.
8. Schneider, R. M.; Plasman, K. *Review of Educational Research*, **2011**, *81*, 530.
9. Fraut, M. Developing professional knowledge and competence.; Falmer Press, London, 1994; p 35.
10. Park, S.; Oliver, J. S. *Research in Science Education*, **2007**, *38*, 261.
11. Shulman, L. S. *Educational Researcher*, **1986**, *15*, 4.
12. Shulman, L. S. *Harvard Educational Review*, **1987**, *57*, 1.
13. Haidar, A. H. *Journal of Research in Science Teaching*, **1997**, *34*, 181.
14. Van Driel, J. H.; Verloop, N.; de Vos, W. *Journal of Research in Science Teaching*, **1998**, *35*, 673.

15. Gess-Newsome, J. Pedagogical content knowledge: An introduction and orientation. In *Examining pedagogical content knowledge*; Gess-Newsome. J., Lederman, N. G. Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1999; p 3.
16. Grossman, P. L. The making of a teacher: Teacher knowledge and teacher education.; Teachers College Press: Teachers College, Columbia University, 1990; p 6.
17. Barnett, J.; Hodson, D. *Science Education*, **2001**, *85*, 426.
18. Hashweh, M. Z. *Teachers and Teaching*, **2005**, *11*, 273.
19. Lee, E.; Luft, J. A. *International Journal of Science Education*, **2008**, *30*, 1343.
20. Abell, S. K. Research on science teacher knowledge. In *Handbook of Research on Science Education*, Abell, S. K., Lederman, N. G. Eds.; Lawrence Erlbaum Associates Publishers: Mahwah, NJ, 2007; p 1105.
21. Van Dijk, E. M.; Kattmann, U. *Teaching and Teacher Education* **2007**, *23*, 885.
22. Zembal-Saul, C.; Starr, M. L.; Krajcik, J. S. Constructing a framework for elementary science teaching using pedagogical content knowledge. In *Examining pedagogical content knowledge;* Gess-Newsome, J., Lederman, N. G. Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1999; p 237.
23. Abell, S. K.; Meredith, A.; Rogers, P.; Deborah, L. H.; Lee, M. H.; Gagnon, M. J. *Journal of Science Teacher Education*, **2009**, *20*, 77.
24. Hume, A.; Berry, A. *Research in Science Education*, **2011**, *41*, 341.
25. Loughran, J.; Berry, A.; Mulhall, P. Science teaching and science teacher education. In *Understanding and Developing Science Teachers' Pedagogical Content Knowledge Professional Learning*, 2012; p 223.
26. van Driel, J. H.; Berry, A. *Educational Researcher*, **2012**, *41*, 26.
27. Cove, M.; McAdam, J.; McGonigal, J. Mentoring, Teaching and Professional Transformation. In *Threshold Concepts within the Disciplines*; Land, R.; Meyer, J. H. F., Smith, J. Eds.; Sense Publishers: Rotterdam, 2008; p 197.
28. King, C.; Felten, P. *The Journal of Faculty Development*, **2012**, *26*, 5.
29. Magnusson, S.; Krajcik, L.; Borko, H. Nature, sources and development of pedagogical content knowledge. In *Examining pedagogical content knowledge*; Gess-Newsome, J., Lederman, N. G. Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1999; p 95.
30. Appleton, K. *Journal of Science Teacher Education*, **2008**, *19*, 523.
31. Mulholland, J.; Wallace, J. *Teaching and Teacher Education*, **2001**, *17*, 243.
32. Johnston, J.; Ahtee, M. *Teaching and Teacher Education*, **2006**, *22*, 503.
33. De Jong, O.; Veal, W. R.; Van Driel, J. H. Exploring chemistry teachers' knowledge base. In *Chemical education: Towards research-based practice*; Springer: The Netherlands, 2003; p 369.
34. Park, E.; Light, G. Identifying potential threshold concept in nanoscience and technology: Engaging theory in the service of practice. In *Threshold concepts and transformational Learning;* Meyer, J. H. F., Land, R., Baillie, C. Eds.; Sense Publishers: The Netherlands, 2010; p 259.
35. van Gennep, A. The rites of passage, London: Routledge and Kegan Paul. (1960).
36. Commons, M. L.; Miller, P. M.; Kuhn, D., *Child Development*, **1982**, *53*, 1058.
37. Richards, F. A.; Commons, M. L. Systematic, metasystematic, and cross-paradigmatic reasoning: A case for stages of reasoning beyond formal operations. In *Beyond formal operations*; Commons, M. L., Richards, F. A., Armon, C., Eds.; Praeger Publishers: New York, 1984; p 92.
38. Kallio, E. *Journal of Adult Development*, **1995**, *2*, 187.
39. Schon, D. A. The reflective practitioner: How professional think in action. Basic Books, Inc. New York, 1983.
40. Tamir, P. *Teaching and Teacher Education*, **1988**, *4*, 99.
41. Smith, D. C.; Neale, D. C. *Teaching and Teacher Education*, **1989**, *5*, 1.
42. Feiman-Nemser, S.; Parker, M. B. *Journal of Teacher Education*, **1990**, *41*, 32.
43. Carlsen, W. S. *Science Education*, **1991**, *75*, 631.
44. Cochran, K. F.; Jones, L. The subject matter knowledge of preservice science teachers. In *International Handbook of Science Education*; Fraser, B. J., Tobin, K. G. Eds.; 1998; p 707.
45. Geddis, A. N. *International Journal of Science Education*, **1993**, *15*, 673.
46. Morine-Dershimer, G. *Journal of Teacher Education*, **1989**, *40*, 46.
47. Ball, D. L.; McDiarmid, G. W. The subject matter preparation of teachers; In *Handbook of Research on Teacher Education*; Houston, W. R., Ed.; Macmillan: New York, 1990; p 437.
48. Kennedy, M. Trends and Issues in teachers' subject matter knowledge (Trends and Issues paper No1), ERIC Clearinghouse on Teacher Education, Washington, DC. (ERIC ED 322100), 1990.
49. Wenner, G. *Journal of Science Education and Technology*, **1993**, *2*, 461.

Appendix A

5. What are the three most important concepts in high school chemistry?

6. Why do you think that each concept is important for learning high school chemistry?

7. What were the three most difficult chemistry concepts for you when you were in high school?

8. Why do you think that each concept was difficult for you to understand?

Omitted a paragraph including the definition, features, and specifics of threshold concepts

9. Based on your own experience of learning or teaching in high school, what do you believe are potential threshold concepts in high school chemistry?

Why do you think that each concept is a threshold concept in learning chemistry?

10. Could you explain your mastery experience (or moment of awareness) of each threshold concept in detail?

If you had the moment when you were learning, could you explain about it in detail?

If you had the moment when you were teaching or doing a teaching-related activity, could you explain about it in detail?

11. (1) Did your experience with threshold concepts have any impact on you (view on science or learning science)?

(2) How does your experience with threshold concepts affect your teaching or your work?

(3) When you are teaching the threshold concepts, if you have the experience of overcoming the threshold barrier, how do you teach? Is there any difference with teaching other concepts?

Appendix B

12. What are the values of applying threshold concepts to the development of instruction and curriculum materials?