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University Students' Understanding of Chemistry Processes and the Quality of Evidence in their Written Arguments

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We have developed a process-oriented chemistry laboratory curriculum for non-science majors. The purpose of this study is both to explore university students' understanding of chemistry processes and to evaluate the quality of evidence students use to support their claims regarding chemistry processes in a process-oriented chemistry laboratory course. The data were collected from four classes offered during the first two semesters in which the new curriculum was implemented. We analyzed students' written laboratory reports, which included the components of claims, evidence, and reflection, to investigate their understanding of the process skills required in knowledge construction in chemistry. We also evaluated the quality of evidence the students used to support their claims regarding chemistry processes by using five-level criteria which we developed. The findings of this study show that a process-oriented laboratory curriculum contributes to developing university students' understanding of chemistry processes and the ability to link appropriate and sufficient evidence to their claims. The findings of this study also imply that there are specific types of process skills which are unique or more necessary for chemistry research, and these skills can be developed through a process-oriented chemistry laboratory curriculum.

Keywords: process-oriented chemistry laboratory curriculum; reasoning ability; science process skills; written arguments

INTRODUCTION

Science process skills, defined as "what scientists do when they study and investigate problems" (Funk, Okey, Fiel, Jaus, & Sprague, 1979), have become an important component of science curricula at all levels, based on the proposition that

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acquiring them should be one of the major goals of science instruction (Anderson, 2002; National Research Council [NRC], 1996; Padilla, Okey, & Dillashow, 1983). More specifically, these skills have been categorized into basic process skills (i.e., observing, classifying, communicating, measuring, predicting, and inferring) and integrated process skills (i.e., identifying and controlling variables, formulating and testing hypotheses, interpreting data, defining operationally, experimenting, and constructing models) (Martin, 2006; Veal, Taylor & Rogers, 2009).

In science curricula, science process skills refer to the intellectual skills or science processes which are required by students to practice and understand science (Oloruntegbe, 2010). In the new Science Framework for K-12 Science Education, these process skills are merged into the practices that scientists employ as they investigate and build theories about our world (National Research Council [NRC], 2012). In this study, we use the term chemistry processes and define it as the process skills that chemists employ to construct chemistry knowledge.

An introductory chemistry laboratory course is the first opportunity for most students to gain an understanding of what chemists do to construct chemistry knowledge, and what skills are required in the process of this knowledge construction. However, the traditional recipe-style introductory chemistry laboratory curriculum does not emphasize these chemistry processes as its main learning objective. We have developed a process-oriented chemistry laboratory curriculum aiming to provide the framework of laboratory activities which engage students in authentic inquiry experiences. The main goal of this curriculum is to help students develop an understanding of the process of knowledge construction in chemistry by encouraging students' self-directed learning and collaboration with peers.

State of the literature

- It has been assumed that process skills are general and content-independent. Few studies have explored the science process skills that are specific to each discipline.
- Constructing scientific arguments that link evidence to claims has been accepted as an essential skill that defines scientific reasoning ability. However, students often have difficulty selecting evidence and using it to support their claims.
- Science process skills are related to aspects of formal reasoning ability, such as correlation, combination, probability, proportional logic, etc.

Contribution of this paper to the literature

- There are specific types of process skills (i.e., chemistry processes) which are unique or more necessary for chemistry research.
- The understanding of chemistry processes can be developed through a process-oriented chemistry laboratory curriculum. Collaboration and discussion with peers can contribute to improving university students' understanding of chemistry processes.
- The process-oriented laboratory curriculum improves students' understanding of science process skills that are required in constructing chemistry knowledge, which stimulates further development of students' ability to use appropriate and sufficient evidence to support their claims.

The laboratory activities were developed based on eight target topics (i.e., observation, collecting/sharing data, organizing data, synthesizing, separating substance, language and symbolism/classifying, quantitative data, and employing technology).

Constructing scientific arguments that link evidence to claims has been accepted as an essential skill that defines scientific reasoning ability (National Research Council [NRC], 1996; Osborne, Erduran, Simon, 2004; Sandoval & Millwood, 2005; Wellington & Osborne, 2001). Previous studies, which have explored students' reasoning ability in terms of linking evidence and claim, reported that students often have difficulty selecting evidence and using it to support their claims (Keys, 1999; Sandoval & Millwood, 2005).

Padilla and his colleagues' study (1983) has indicated that reasoning ability that connects evidence to a claim is related to science process skills. However, few studies have explored the relationship between science process skills and students' ability to support their claims with evidence drawn from data. Most previous research has asserted that science process skills are related to aspects of formal reasoning ability, such as correlation, combination, probability, proportional logic, etc. (Padilla, Okey, & Dillashaw, 1983; Tobin & Capie, 1982). We anticipated that our process-oriented curriculum would improve students' understanding of chemistry processes that are required in constructing chemistry knowledge, which would stimulate further development of students' ability to use appropriate and sufficient evidence to support their claims.

The purpose of this study was both to explore university students' understanding of chemistry processes -- i.e., understanding how chemical knowledge and products are constructed and used -- and evaluate the quality of evidence students used to support their claims in a process-oriented chemistry laboratory course.

First, we aimed to investigate how university students understand chemistry processes, instead of measuring their performance of process skills during the laboratory activities. This choice of research focus is based on the assertion that a conceptual understanding of science process skills highly correlates to the performance of those skills in a specific topic area (Barbosa & Alexander, 2004). We also believe that an understanding of chemistry processes is a significant part of scientific practices. This position is reinforced by the fact that the Science Framework for K-12 Science Education adopts the term "practices" rather than "skills" in order to "emphasize that engaging in scientific investigation requires not only skills but also knowledge that is specific to each practice." (National Research Council [NRC], 2012, p.30).

Second, using criteria we developed, we assessed the quality of evidence used by students to examine if our process-oriented curriculum could stimulate reasoning ability for them to use appropriate and sufficient evidence to support their claims. We analyzed written laboratory reports, including the components of claim, evidence, and reflection. We assumed that students' claims and reflection would reveal their understanding of the processes required in knowledge construction in chemistry.

The following questions guided this study:

1) What knowledge of chemistry processes do university students develop through a process-oriented chemistry laboratory course?
2) How does the quality of students' evidence used to support claims improve throughout the course?

THEORETICAL BACKGROUND

Science process skills

Science process skills are transferrable intellectual skills that provide a foundation of inquiry as well as improve student understanding of subject matter (Anderson, 2002; Scharmann, 1989). Previous studies have been conducted to examine the benefits of teaching science process skills (Brotherton & Preece, 1996; Sharmann, 1989), the effect of a specific curriculum and instruction on science process skills (Goh, Toh, & Chia, 1989; Padilla, Okey, & Garrad, 1984; Veal, et al., 2009), and the relationship between science process skills and formal reasoning ability (Padilla, et al., 1983; Tobin & Capie, 1982; Yeany, Yap, & Padilla, 1986), as well as to develop instruments to assess students' science process skills (Burns, Okey, & Wise, 1985; Dillashaw & Okey, 1980; Feyzioglu, Demirdag, Akyildiz, & Altun, 2012; Oloruntegbe, 2010; Tobin & Capie, 1982).

Most of these studies were grounded in the assumption that reasoning skills, including science process skills, are general and domain independent (Roth & Roychoudhury, 1993; Simon, 1981). On the other hand, this basic assumption has been subject to criticism because important aspects of cognitive skills are tied to specific contexts, such as the problem's physical and conceptual structure (Rogoff, 1984; Roth & Roychoudhury, 1993). This criticism assumes that specific process skills might be more essential for certain disciplines over others. However, few studies have explored the science process skills that are specific to each discipline (Roth & Roychoudhury, 1993).

Some studies have examined students' science process skills in specific contexts, in particular, a laboratory setting has been assumed to be an appropriate context in which students learn and use science process skills to solve problems in a hands-on (or "minds-on") manner by applying knowledge they have learned in lecture (Roth & Roychoudhury, 1993; Veal et al., 2009). Roth and Roychoudhury (1993) examined the development of high school students' science process skills in the context of open-ended laboratory activities and concluded that participants' higher-order process skills improved over the course of their study in such areas as identifying variables, hypothesizing, operationally defining, designing experiments, and interpreting data through inquiry-based laboratory experiences. Their students engaged in open-ended inquiries to seek answers to their own research questions by both planning and designing experiments and collecting, transforming, and interpreting the data. Even though this study was conducted at the high school level, it provides insight for college laboratory curricula, in that an authentic inquiry context in science laboratories is effective in developing higher-order science process skills. In a study investigating the effects of student self-reflection on the development of process skills in a general chemistry course, Veal et al. (2009) identified six context-dependent process skills: lighting a Bunsen burner, measuring, observing, communicating, pipetting, and titrating.

Written argument: claim and evidence

Written arguments aimed to inform and persuade other people about the validity of a particular claim are essential to communication in scientific communities (Choi, Hand, & Greenbowe, 2013). Researchers have suggested that constructing written arguments based on claim and evidence is an important part of scientific inquiry in science education (Osborne et al., 2004; Sandoval & Millwood, 2005). However, students have difficulty identifying and conveying appropriate and sufficient evidence to support their claims, often failing to articulate how specific data relate to particular claims (Sandoval & Millwood, 2005). They tend not to reflect on the meaning of data, and thus do not understand how to relate observations to knowledge claims (Keys, 1999).

While researchers have argued for the importance of written arguments in scientific inquiries, students' ability to make connections between claim and evidence has not been widely explored in the college laboratory setting. Choi et al. (2013) examined college students' written arguments that appear in a general chemistry laboratory course. The researchers concluded that the evidence and the claims-evidence relationship components were the most significant predictors of student argument scores. Walker and Sampson (2013) developed an instructional model for a college general chemistry laboratory course (i.e., Argument Driven Inquiry) which engages students in argument and critique. The students who engaged in a series of argument-driven lab activities showed significant improvement in their ability to use evidence in ways that supported their claims.

Some researchers, asserting that argument is the main feature of authentic scientific inquiry, have sought to develop an alternative framework to evaluate student written arguments in the context of science learning, including inquiry and inquiry-based laboratory settings. In Katchevich and colleagues' study (2013), the components of written arguments analyzed in the students' laboratory reports were claim, evidence, and scientific explanation. Choi et al. (2013) evaluated seven components of written arguments: questions, claims, questions-claims relationships, evidence, claims-evidence relationships, use of multiple modal representations, and reflection. Walker and Sampson (2013) evaluated the quality of students' written arguments using five criteria: providing well-articulated, adequate, and accurate claims; presenting appropriate and genuine evidence; providing valid and reliable evidence; providing sufficient and appropriate rationales; and comparing findings with other groups. Sandoval and Millwood (2005) evaluated high school students' written arguments in terms of the conceptual adequacy of explanatory claims, the sufficiency of the cited evidence for claims, and students' rhetorical use of specific inscriptions in their arguments.

In this study, we developed a framework in an inductive way to assess the quality of students' evidence based on students' written arguments appearing in their lab reports. However, the criteria used in previous studies also played a role as a theoretical framework when we developed our criteria. The underlying idea to determine the quality of evidence was whether the evidence students provided was relevant, appropriate, accurate, and sufficient enough to support their claims (Choi et al., 2013; Sampson, & Gleim, 2009; Sandoval and Millwood, 2005; Walker & Sampson, 2013).

METHODS

Research design & context

This study used qualitative data as a primary data source employing a "basic qualitative study design" (Merriam, 1998, p. 11). However, quantitative analysis was also used to elaborate upon or triangulate with those from the qualitative analysis. The context of this study was a 1-credit introductory chemistry laboratory course that consisted of a weekly three-hour series of experiments at a university in the Midwestern United States. The laboratory course was combined with a 3-credit general chemistry lecture course for non-science majors. The laboratory course was taught by the third author, who developed the process-oriented laboratory curriculum. The third author had previously developed several college chemistry lecture/laboratory curricula for non-science majors, as well as K-5 elementary science curricula. The process-oriented laboratory curriculum was examined by chemistry faculty and approved at the department faculty meeting.

Process-oriented laboratory curriculum

The main goal of the curriculum was to provide a framework for constructing a comprehensive and coherent progression of activities to provide authentic experiences for what it means to do chemistry, understand chemistry, and be a chemist. Table 1 shows the main ideas, rationales, expected outcomes, and activities we wanted students to experience through the curriculum. Table 2 shows the eight experiments comprising this curriculum and the laboratory schedule for the semester. This curriculum used an inquiry-based approach, which allowed students through their own thinking, to discover procedures, patterns, and principles that are the basis for the gradual accumulation of chemical knowledge.

Data collection

The data were collected from four classes offered during the first two semesters of the implementation of the new curriculum. Most participants enrolled in the course were from a nursing or technology program. All the laboratory activities were conducted collaboratively in groups of two or whole-class discussions. The students were randomly assigned to groups on the first day of class. Before each class, students were asked to perform pre-laboratory tasks or to answer questions related to that day's experiment. At the beginning of each experiment, students received a written outline of suggested activities. Through class discussion or group discussion, students decided what needed to be explored and how to design an experiment to solve the problem. Based on the design, data collection and analysis were conducted in each group, and the students shared the data and interpretation with the other groups during class discussion.

Table 1. Process-oriented laboratory curriculum framework

Big Idea: The fundamental principle of how chemistry acquires the information and products we want students to experience.	**Rationale**: The mindset we want students to develop regarding the function of chemistry in society.	**Outcome:** The cognitive structure we hope to develop and/or strengthen.	**Activity**: What the students will do to facilitate the acquisition of the desired big idea, mindset, and outcome.
1. Observation is a fundamental skill necessary to acquire useful chemical information.	The development of useful chemical knowledge begins with the compilation of detailed observations.	Students are prompted to use **reflective awareness** to develop **observation skills** for **gathering information**.	**Experiment #1:** Record observations of reactions of chemicals labeled A, B, etc., critique observations using a provided format, then collect additional observations using the new criteria.
2. The documentation and sharing of experiments and results can lead to the accumulation of useful chemical information.	The recording of detailed observations and the sharing of that information has allowed chemical knowledge to grow. Chemists can access this shared information and use it in solving problems.	a) Students will establish the procedures for **gathering information** so that all data can be **compared**. b) Students are prompted to develop and use **organizational frameworks** for displaying data and **finding patterns**. c) Students will be prompted to **evaluate** the compiled data and use **reflective awareness** to **solve a problem**.	**Experiment #2 a,b,c,d:** Class works together as a team to collect and compile information on a variety of solids. Each pair collects only a subset of the data which must then be validated by another pair before it is shared with the class. The data is organized by the class into a table and flow diagram. Finally, a set of unlabeled chemicals must be tested using the compiled data to determine if it is one of the solids previously studied.
3. Developing procedures for synthesizing a desired product often require repeated experiments that manipulate the variables in a controlled way.	The earliest examples of chemistry were associated with finding the recipes for accidentally discovered substances. A fundamental function of chemistry is refining and documenting procedures to produce new products.	Students will need to use **constancy and change** observations and **cause-effect relationships** to work toward a product.	**Experiment #3:** Starting with a vague description of how pioneers made soap, students will experiment to develop a recipe for making soap from rendered fat and lye from soaked ashes.
4. Separation procedures allow us to isolate pure substances from mixtures. Pure substances can then be characterized and identified.	In order to accumulate knowledge of individual chemicals, samples first need to be separated to make sure that they are pure substances.	Students will experience the **significance and function** of some of the tools needed to facilitate the collection of chemical data.	**Experiment #4:** Students will separate and then identify chemicals using: solubility, fractional distillation, and chemical replacement.
5. Properties can be used to group and classify pure compounds. 6. The symbolism and terminology used in chemistry conveys specific and detailed information. (These two ideas merge and weave throughout the experience.)	Learning in any discipline requires knowledge of the language and symbols that are used to express and communicate that discipline. One way chemistry manages to deal with the huge quantity of chemical information is to group similar compounds into labeled classifications.	Students will have to use **cause-effect relationships** in order to **classify** chemicals. Students will need to connect substances and their properties with their **symbolic representations** in order to **make connections** to the established **coding systems** for chemicals.	**Experiment #5-6:** Students will access internet sources to find additional information on the chemicals, determine the symbols and names for the chemicals, as well as the terminology used to classify chemicals as belonging to specific groups. Culminates in students writing double displacement reactions for observed reactions from Exp. 2.

7. Quantitative data yields additional properties for classifying and identifying chemicals	Careful measurements can result in the discovery of additional properties useful in identifying and characterizing compounds.	a) Students will establish the procedures for **gathering quantitative information** so that all data can be **compared**. b) Students will experience the significance of **multiple measurements and statistical analysis** of multiple measurements to arrive at best values. c) Students are prompted to develop and use **organizational frameworks** for displaying data and **finding patterns**. d) Students will be prompted to **evaluate** the compiled data and use **reflective awareness** to **solve a problem**.	**Experiment #7:** Measurement and density lab that utilizes density to identify visually similar objects. Also serves to elucidate the explanation of why some things float and others sink in water.
8. Technology hasenhanced our methods of identification of chemicals. Technology also allow us to determine quantities of chemicals present in samples	Technology expands our chemical knowledge by allowing us to "see" things our eyes cannot and measure things our hands cannot.	Students will experience the **significance and function** of technology as a tool in expanding our ability to identify and quantify chemicals in a sample.	**Experiment #8:** Students will use a Spec 20 to explore the use of technology and light in identifying chemicals previously studied in Exp. 2. They will also determine if this technology can be useful in measuring quantities of chemicals previously studied in Exp. 2.

Table 2. Laboratory schedule

Week	Activity	Target Topic (Code)
1	Introduction	Check-In, Safety
2	Experiment #1	Observation (O)
3-6	Experiment #2	Collecting (CD)/Sharing (SD)/Organizing (OD) data
7	Experiment #3	Synthesizing: Discovering the recipe for soap (SYN)
8	Experiment #4	Separating substances (SE)
9	Midterm evaluation	
10-11	Experiment #5/#6	The language and symbolism of chemistry/Classifying (SYB)
12	Experiment #7	The value of Quantitative data (QT)
13-14	Experiment #8	Employing technology (TE)
15	Final Evaluation	

Participants also wrote laboratory reports on Blackboard (the web-based education tool) consisting of data, interpretation of the data, claim, and evidence regarding chemistry content (i.e., an in-lab report). After class, each group was required to write a post-laboratory report on Blackboard, including claim and evidence regarding chemistry processes, and reflection (i.e., a post-lab report). In the post-lab report, students were asked to generate claims about how chemical knowledge and products are acquired, and to describe what evidence they could provide to support their claims. They were also asked to reflect upon their learning. For example, for Experiment 1 about observation, each group was asked to respond to the following questions: 1) From this experience, what claim or statement can you make about how chemists collect information to build a knowledge base to solve problems? 2) Using this experience, what is your evidence for the above statement? 3) As a result of this laboratory experience, what have you learned about the things that are important when observing and recording chemical observations? Before the next class, an instructor provided online feedback and evaluation for each group, outlining the strengths and weaknesses of the report.

The primary data for this study were claim, evidence, and reflection related to chemistry processes in the post-lab report. We did not include students' claims, evidence, or reflection regarding chemistry content from in-lab reports as primary data. However, the data from in-lab reports were used as supplementary data for understanding students' claims, evidence, and reflection regarding chemistry processes in the post-lab report. At the end of the semester, we also asked students to reflect on their experiences from the course.

The laboratory reports were collected from 50 groups (with most groups consisting of two students) from four class sections during two semesters. The total number of post-lab reports required from each group throughout the semester was 11. However, due to absence or incomplete participation, the total number of laboratory reports collected for analysis was 512, from four class sections during the two semesters.

Data analysis

Data analysis was conducted separately with regard to the understanding of chemistry processes and the quality of evidence. All data analysis was done by the first and second authors of this study. In order to increase the trustworthiness of data analysis, the identified codes, patterns and categories were also discussed with the third author, who developed and taught this curriculum.

Understanding of chemistry processes

The claims, evidence and reflection in the students' post-laboratory reports were analyzed to investigate their understanding of chemistry processes using the constant comparative method (Glaser & Strauss, 1967; Strauss & Corbin, 1990). The first step of data analysis was identifying all the initial codes regarding students' understanding of chemistry processes. After thoroughly and repeatedly reading and reviewing the data, the researchers assigned initial codes separately to each claim, piece of evidence, and segment of the reflections which showed student understanding of chemistry processes. The researchers then met to discuss any variation in coding and determine the initial codes. By comparing and contrasting the initial codes, the researchers identified the patterns of students' understanding (called "knowledge patterns" hereafter) regarding chemistry processes. The identified knowledge patterns were organized into eight pre-determined categories (i.e., observation, collecting/sharing data, organizing data, synthesizing, separating substance, language and symbolism/classifying, quantitative data, and employing technology).

We named these eight categories "Target topics" because they represent the basic ideas of the process-oriented laboratory curriculum framework, which we wanted students to improve upon throughout the semester (see Table 1).

All the data (i.e., claims, evidence, and reflections in the students' laboratory reports) were re-analyzed by the two researchers separately using the identified knowledge patterns. The intra-rater reliability of identifying knowledge patterns was 83%. The researchers then met to discuss any variation in finding knowledge patterns, and finalized them. In order to examine the development of the students' understanding regarding chemistry processes, in each target topic, we counted the number of groups showing each knowledge pattern in their laboratory reports. We present all the knowledge patterns and target topics regarding chemistry processes in the Findings section (see Table 4). We identified a total of 44 knowledge patterns, which were categorized into eight target topics.

The quality of evidence

We developed a five-level analytical framework to evaluate the quality of the evidence students linked to support their claims in an inductive way. While comparing and contrasting all the evidence in the students' laboratory reports from two classes, the first and second author separately identified initial criteria for identifying different levels of evidence. Using this initial criteria, the researchers evaluated students' evidence from the two classes. Next, through discussion, the researchers modified some criteria for simplicity and clarity. The researchers tried to avoid ambiguous criteria which were likely to involve the evaluator's subjectivity and then they finalized the five level criteria.

Using the finalized framework, students' evidence from four classes was evaluated and categorized into five levels based on quality. The initial intra-rater reliability in evaluating students' evidence was 86%. The researchers then met to discuss until they reached agreement. The number of pieces of evidence categorized into each level was counted in each target topic and compared across the semester. Table 3 shows the five-level criteria used to evaluate the evidence students used to support their claims, along with examples.

FINDINGS

Knowledge patterns of chemistry processes

Throughout the semester, students developed various knowledge patterns, summarized in Table 4. A total of 44 knowledge patterns regarding chemistry processes were identified and categorized into eight target topics: observation, collecting/sharing data, organizing data, synthesizing, separating substances, language and symbolism/classifying, quantitative data, and employing technology. These eight target topics represent the main ideas of the process-oriented laboratory curriculum framework (see Table 1).

In most cases, each group revealed more than one knowledge pattern in each target topic. We counted the number of groups which revealed each knowledge

Table 3. Criteria to evaluate the quality of students' evidence and example

Level	Criteria	Example
L1	Evidence is not related to claim	*Claim*: You have to have organization in order to have the right results come out. (OD1*) *Evidence*: You have to be very specific in the things that you say because it could be thought to be something different than what it really is.
L2	Evidence is related to claim	*Claim*: When collecting and organizing data, using a data sheet that is neatly organized is a good way to collect and analyze data so you can easily find and share information with others (OD4*) *Evidence:* We used a sheet for our experiments to neatly organize our data so we can find share information with others easily. We had firsthand experience of how much it helps to be organized and clear.
L3	Criteria for L2 & Evidence is based on specific data or events from the lab activity	*Claim*: After testing different experiments, chemists use the information that was collected to build their knowledge in order to solve the problem (SD2*) *Evidence*: By using different liquid and solid chemicals in our test tubes we collected different observations. There were some that seemed to disappear completely in the liquids and others that corroded. By seeing these results we enhanced our knowledge base of what these chemicals are capable of.
L4	Criteria for L3 & Data or events are explained including specific information such as chemicals' name, color etc.	*Claim*: Separating substances is essential for chemistry because this process let me know what I have and allows me to test substances individual (SE1*) *Evidence*: Separating the substances allowed us to narrow our choices for the identity of the liquid. By using the still we determined that one of the substances was ethanol. Then by cooling the remaining liquid, we cooled it and found a solid. Finally by using filter paper, we separated the solid substances from the liquid. Then I tested both substances. We came to the conclusion that it was Lauric because it floats in HCl.
L5	Criteria for L4 & Explanation of the data/events includes quantitative data.	*Claim*: Separation is essential because: just because a liquid is clear and colorless does not mean that it is pure. (SE5*) *Evidence*: Our evidence is from the experiment we just did. When we first started out we thought that mixture 2 was a pure substance because it was clear, colorless, and odorless, but we were mistaken because when we did our distillation and some liquid came out at about a temperature of 78-80 degrees and the second liquid came out at around 100 degrees, but there was still some liquid left over. We then left that liquid on cold ice and found out that there was a solid in the liquid because it turned a milky white color. We later used a filter out the solid and liquid and found out the solid was Lauric and the liquid was water by doing our solubility test from experiment 2.

** Acronyms are found in Table 4*

Table 4. Knowledge patterns of chemistry processes

Target topics (Exp.)	**# (%) of groups/Knowledge patterns**						
Observation (Exp.1)	O1	O2	O3	O4			
	40(80.0)	34(68.0)	22(44.0)	12(24.0)			
	O1: Observation/descriptions of observation should be detailed and exact. O2: Observation should use all the appropriate senses (heat, color, smell, etc.). O3: Observation should focus on the change of reaction. O4: Observation should include a time factor.						
Collecting/ Sharing Data (Exp.2)	CD1	CD2	CD3	CD4	SD1	SD2	SD3
	44(88.0)	40(80.0)	40(80.0)	36(72.0)	34(68.0)	18(36.0)	12(24.0)
	CD1. Following a stipulated procedure (e.g. exact measurement, same steps) is vital in experimenting to get correct information/outcomes. CD2. Repeated test/verification is necessary to minimize the possibility of error. CD3. Variables should be controlled to get uniform outcomes for comparison purposes. CD4: Collecting accurate data influence on next phase data collection/correct outcomes. SD1. Scientists build knowledge through collaboration with other scientists such as sharing observations/ideas. SD2. Collected data/information forms the basis for solving the future problems/getting new knowledge. SD3. There are various ways of collecting organizing data/solving a problem.						
Organizing Data (Exp.2)	OD1	OD2	OD3	OD4	OD5		
	23(46.0)	20(40.0)	20(40.0)	14(28.0)	4(8.0)		
	OD1. Data should be well organized to contribute to getting correct outcomes/new knowledge. OD2. Data should be well organized to make them easy to understand. OD3. Data should be well organized to contribute to further steps of data collection. OD4. Data should be well organized to help communication. OD5. Chemistry data are collected/organized in an inductive way.						
Synthesizing (Exp.3)	SYN1	SYN2	SYN3	SYN4	SYN5	SYN6	
	34(68.0)	32(64.0)	32(64.0)	14(28.0)	12(24.0)	6(12.0)	
	SYN1. Discovery of things in chemistry is often unplanned/by accident. SYN2. Controlling/monitoring variables are needed to synthesize desired products. SYN3. Understanding cause-effect relationship in synthesizing helps chemists discover a way to get final products. SYN4. Development of scientific knowledge is a result of human endeavor. SYN5. Chemists synthesize new products using things that already exist. SYN6. Starting from small quantities of chemicals is more efficient in synthesizing products.						
Separating Substances (Exp.4)	SE1	SE2	SE3	SE4	SE5	SE6	
	40(80.0)	26(52.0)	24(48.0)	18(36.0)	4(8.0)	2(4.0)	
	SE1. Separation is an essential step before any testing to identify substances. SE2. Separation is conducted based on the fact that each element/compound has different properties. SE3. Separation is essential to get pure substance. SE4. Well equipped/designed tools (e.g. fractional distillation) are required for separation. SE5. Separation procedures are essential because chemists cannot judge whether the substance is pure by observing outward appearance. SE6. Chemists try to find the better way of separating chemicals.						
Language and Symbolism/Classifying (Exp.5/6)	SYB1	SYB2	SYB3	SYB4	SYB5		
	36(72.0)	32(64.0)	14(28.0)	8(16.0)	8(16.0)		
	SYB1. Chemistry's language and symbolism (i.e. Chemical formula, chemical equation) can be used to identify and classify the chemicals. SYB2. Chemistry's language and symbolism can be used to show the nature of chemicals/the way chemicals react with other substances. SYB3. Chemistry's use of systematic language and symbolism helps chemists communicate with each other. SYB4. Chemistry's language and symbolism provides information about what to do (in the process of chemical synthesizing) in order to get expected outcomes.						

Quantitative Data (Exp.7)	QT1	QT2	QT3	QT4	QT5	QT6
	36(72.0)	32(64.0)	30(60.0)	26(52.0)	20(40.0)	14(28.0)
	QT1. Repeated measurements allow for the calculation of averages to better represent the results of the measurements and calculations. QT2. Measured quantitative data has an inherent degree of uncertainty. QT3. A wide variety of special tools and methods are used to collect quantitative data. QT4. Calculated data should be reported using significant figures to represent the degree of uncertainty of the measured value. QT5. Quantitative data can be used to identify the properties of substances not obtainable through qualitative means. QT6. The measuring tools must be used correctly and read to the last obtainable digit.					
Employing Technology (Exp.8)	TE1	TE2	TE3	TE4	TE5	
	36(72.0)	32(64.0)	14(28.0)	6(12.0)	6(12.0)	
	TE1. Technology contributes to expanding current knowledge/generating new knowledge by providing high quality data/products. TE2. Technology helps chemists be able to gain data that cannot be obtainable without it. TE3. Technology allows chemists to be more efficient (e.g. faster and more accurate) in conducting experiments/getting outcomes. TE4. Technology is an ever-changing tool that contributes to the quality of human life. TE5. Technology cannot work without human effort.					

pattern in their laboratory reports in each target topic. For example, 40 out of 50 groups (i.e., 80%) showed the knowledge pattern O1 in their laboratory reports. We also found that the students' knowledge patterns developed in a certain target topic tended to appear in other experiments. However, we did not include these data in this paper. Table 4 includes only the knowledge patterns students developed regarding each target topic. In this section, we describe the students' experience in the activities, and the main knowledge patterns most students developed through the experience.

Observation (O):

The development of useful chemical knowledge begins with the compilation of detailed observations. In Experiment 1, the students observed a series of simple chemical reactions and recorded those observations. They were given guidelines for their first observations to help them become aware of what they already did well, and where they needed to improve in order to refine their observation skills. After this guided reflection, the students observed another series of chemical reactions and recorded the observations. After this activity, 80% of the groups claimed that observation and description of the observation should be detailed and exact (O1). Many groups also described that during observation, they needed to focus on any changes (44%, O3) by using all appropriate senses (68%, O2).

Collecting/sharing data (CD/OD)

The collecting and sharing of data in a scientific community can lead to the accumulation of useful chemical information. In the first part of Experiment 2, the students were asked to identify the properties of given chemicals. In this experiment, a total of 17 chemicals were distributed to the students, and the common names of each chemical were provided. Each group received two or three chemicals, and some groups were given the same chemicals. Through class discussion, the students designed and agreed upon the procedures for data collection (i.e., how to identify the properties of the chemicals) and a format for recording and displaying the data. The students experienced the process of collecting and sharing data, and solved the problem (i.e., identify unknown chemicals) posed in the second part of the experiment by using the data. They discovered that different groups could have different results even though they were testing the same chemicals. Thus, they realized that following a correct procedure and exact observation or measurement is necessary in collecting chemical data

(88%, CD1). They also learned the importance of verification (80%, CD2) and controlling variables, which is required to gain correct data and compare that data with that of other groups (80%, CD3). Regarding data sharing, 34 groups described how scientists build knowledge through collaboration with other scientists, including sharing observations and ideas (68%, SD1).

Organizing data (OD)

Collected information needs to be organized in some systematic way that allows chemists to begin to see patterns which can become tools for guiding and facilitating further investigation. The second part of Experiment 2 started with a class discussion aimed to organize data collected from each group in the first part of the experiment. Through discussion, the students organized all the data into a table and developed a classification flowchart which placed all the chemicals into groups based on similarities. After that, the students used the flowchart to identify unknown chemicals given to each group. In identifying unknown chemicals using the flowchart, the students seemed to realize that well-organized data contribute to obtaining new knowledge (46%, OD1), and can be used for further steps of data collection (40%, OD3). They also stated that well-organized data are easy to understand (40%, OD2).

Synthesizing (SYN)

Developing procedures for synthesizing a desired product is a significant component of what chemistry is all about. The purpose of Experiment 3 was to allow students to experience the process of synthesizing. After reading the story about how soap was made during pioneer times, the students were asked to make soap using fat and a lye solution obtained by soaking and filtering wood ashes. Without any set procedure, each group decided the ratio and amount of each component before they heated their mixtures to make soap. The instructor tested the synthesized soap to see whether it could clean grease off a watch glass. If it couldn't pass the test, the students made alterations to their procedures until it could.

After class, the students were also asked to do some research on Alexander Fleming and the discovery of penicillin. This research, along with reading a story about making soap during pioneer times, seemed to encourage the students to understand that chemical discoveries are often unplanned/by accident (SYN1, 68%). Through the process of making alterations to their soap-making procedures, the students also learned that they only need to change one variable at a time while controlling other variables in order to figure out which variable(s) affected their product (SYN2, 64%). The students also mentioned that understanding cause-effect relationships in synthesizing helps chemists discover ways to obtain final products (SYN3, 64%).

Separating substances (SE)

Finding ways to separate combinations of chemicals is an essential step in being able to identify substances and determine their properties. In Experiment 4, the students were asked to find out how chemicals can be separated from other substances. For the first activity, the sample of mixtures consisting of two liquids and one solid which had been used in the Experiment 2 was given to each group (i.e., ethyl alcohol, water, and lauric acid). Students only knew that these three chemicals had been used in Experiment 2, but they didn't know which chemicals they received. The students separated two different liquids and one solid to a pure form by using fractional distillation and filtration. After separating the three chemicals, the students identified them by using their boiling point and other information from the flowchart developed in Experiment 2. After that, the students performed two more tasks: separation of a mixture of two solids, and separation of elements from compounds using chemical reactions. After these activities, the students described how separation is important in chemistry because it is an essential step to getting pure substance before any testing to identify substances (SE1, 80%; SE3, 48%), and each separation method uses different properties of chemicals (SE2,52%).

Language and Symbolism/classifying (SYB)

In chemistry, the symbols are used to define the substances and any changes that take place. The purpose of Experiments 5 and 6 was to provide the students opportunities to understand the system of symbols and the language of chemistry. The names the students used for the 17 chemicals in Experiment 2 were archaic and/or common names. During Experiment 5, with the 17 chemicals, the students were asked to Web search the official names and symbols established by the International Union of Pure Applied Chemistry (IUPAC). Then, through class discussion, the students looked for the patterns appearing in the chemical names and formulas. They then compared some of those names and symbols with the properties they documented in Experiment 2. Based on the patterns and properties, the students found that there were different ways of classifying chemicals: organic chemicals, inorganic chemicals, metals, nonmetals, acids, bases, etc. This activity encouraged 72% of the groups to realize that chemistry's language and symbolism (i.e., chemical formulas, chemical equations, etc.) can be used to identify and classify the chemicals (SYB1). Experiment 6 asked students to find out how to express the chemical reactions they observed in Experiment 2 by using chemical equations. After this activity, 64% of the groups mentioned that chemistry's language and symbolism can be used to show the nature of chemicals/the way chemicals react with other substances (SYB2).

Quantitative Data (QT)

Quantitative data is potentially valuable information that can be used to discover the properties of substances beyond those obtainable by qualitative observation. For Experiment 7, the students collected quantitative data to solve problems that simple qualitative data observations could not solve. As the first step, each group determined how many types of wood were represented in five wood blocks painted different colors. Next, the students calculated the density of two irregularly shaped rocks. While measuring mass and volume and calculating the density of each object, the students decided how the measured and calculated values should be expressed. They were asked to record each value to the maximum accuracy of the measuring tool. They were also instructed that a calculated value must be recorded to a degree of uncertainty that is consistent with the measured values. Based on the calculated values, the students determined the identities of the objects and clarified the property associated with an object's propensity to sink or float. After this activity, 72% of the groups described that the calculation of averages using repeated measurements better represents the results of the measurements and calculations (QT1). Many groups also mentioned that measured quantitative data have an inherent degree of uncertainty (QT2, 64%), and calculated data should be reported using significant figures to represent the degree of uncertainty of the measured value (52%, QT4). They also realized that a wide variety of special tools and methods are used to collect quantitative data (60%, QT3).

Employing technology (TE)

Technology has expanded chemical knowledge by allowing chemists to "see" things their eyes cannot, and measure things their hands cannot. Experiment 8 provided the students an opportunity to learn what information they could get by using a Spec 20 spectrophotometer. Spectrophotometers show how much light is transmitted through a particular sample at different wavelengths (i.e., what particular colors are absorbed and transmitted). The students collected data (i.e., the percent of transmittance of the light at each wavelength) by using several chemicals used in Experiment 2, and graphed the data using an Excel spreadsheet. The students used the graphs to determine the color of substances invisible to the naked eye in solutions, as well as to determine the concentrations of substances in a mixture. The students also discussed other possible ways of using the spectrophotometer in chemistry research and the role of technology in science. After this activity, 72% of the groups described that technology contributes to expanding current knowledge or generating new knowledge by providing high quality data/products (TE1). Sixty-four percent of the groups mentioned that technology helps chemists gain data that are unobtainable without it (TE2).

The quality of evidence

By using the five-level criteria, we evaluated the quality of evidence that students linked to support their claims about chemistry processes in their laboratory reports. Table 5 compares the total number of pieces of evidence we identified and the percentage/number of each evidence level across the semester. For example, in Experiment 1, 19.4% of the pieces of evidence (among 62) were identified as L1, while only 3.6% of the pieces of evidence (among 56) were identified as L1 in Experiments 5 and 6. There are no data for Experiment 8 because the laboratory report for Experiment 8 only included claims and evidence regarding chemistry content.

We added together L1 and L2, which we identified as lower level evidence, and L4 and L5, which we identified as higher level evidence. We identified the evidence assigned to L1 and L2 as "lower level" because it was not relevant to the claim or did not include any specific data or events. For example, L1 was assigned in cases where the students described any situation or statement not related to the claim, as they didn't understand the meaning of the evidence. L2 was assigned in cases where the students just paraphrased their claim or described their rationales for why they picked the claim without providing specific data or events. Providing relevant and appropriate evidence has been considered an important aspect in evaluating students' written arguments (Choi et al, 2013; Walker & Sampson, 2013). The pieces of evidence assigned to L4 and L5 were identified as "higher level", in that they provided relevant and appropriate evidence along with more sufficient information such as specific qualitative and quantitative data. The sufficiency of evidence cited to support claims has been used as a criterion for evaluating students' written arguments (Sandoval & Millwood, 2005; Choi et al., 2013).

Figure 1 shows the change in percentage of the lower level evidence (i.e., L1& l2) and higher level evidence (L4& L5) throughout the semester. We conclude that the percentage of higher level evidence tends to increase, while that of lower level evidence tends to decrease, as shown across the experiments. That is, as students conducted more experiments, they tended to use lower level evidence less frequently and higher level evidence more frequently.

Table 5. The change in evidence levels

	Total # of Evi.	**L1 %(#)**	**L2 %(#)**	**L3 %(#)**	**L4 %(#)**	**L5 %(#)**	**L1 & L2 %(#)**	**L4 & L5 %(#)**
Exp. 1 (O)	62	19.4 (12)	51.6(32)	29.0(18)	0(0)	0(0)	71.0(44)	0(0)
Exp. 2a (CD/SD)	126	7.9(10)	28.6(36)	47.6(60)	15.9(20)	0(0)	36.5(46)	15.9(20)
Exp. 2b (OD)	116	3.4(4)	44.8(52)	36.2(42)	15.5(18)	0(0)	48.2(56)	15.5(18)
Exp. 3 (SYN)	76	0(0)	26.3(20)	23.7(18)	44.7(34)	5.3(4)	26.3(20)	50.0(38)
Exp. 4 (SE)	82	0(0)	19.5(16)	34.1(28)	34.1(28)	12.2(10)	19.5(16)	46.3(38)
Exp. 5/6 (SYB)	56	3.6(2)	10.7(6)	28.6(16)	53.6(30)	3.6(2)	14.3(8)	57.2(32)
Exp. 7. (QT)	60	0(0)	6.7(4)	33.3(20)	53.3(32)	6.7(4)	6.7(4)	60.0(36)

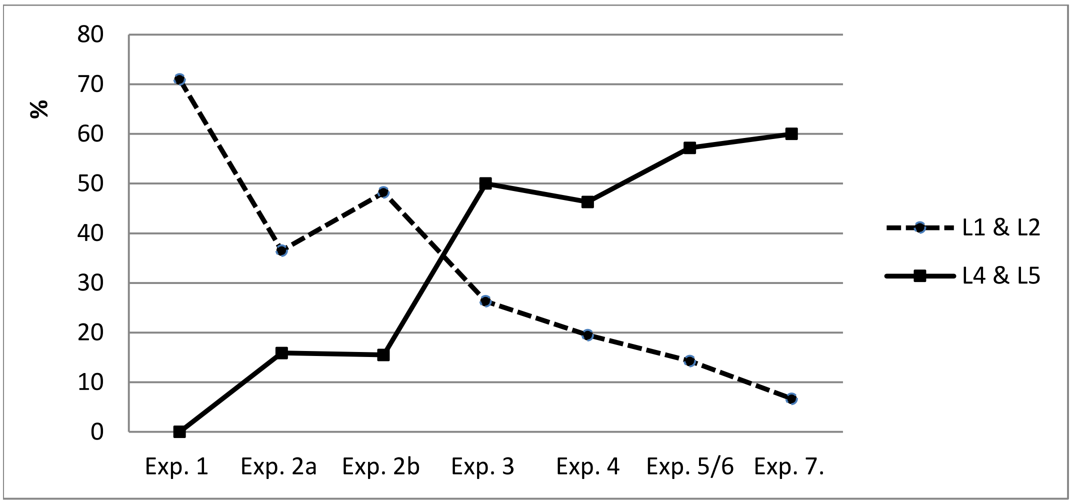

Figure 1. The changes in use of lower and higher level evidence

DISCUSSION/IMPLICATIONS

We analyzed university students' written laboratory reports from the process-oriented laboratory course to investigate their understanding of the process skills required in knowledge construction in chemistry. We also evaluated the quality of evidence students used to support their claims regarding chemistry processes by using our five-level criteria. Findings of this study show that a process-oriented laboratory curriculum contributes to developing university students' understanding of chemistry processes and ability to link appropriate and sufficient evidence to their claims.

The students developed various knowledge patterns regarding chemistry processes throughout the semester. The identified knowledge patterns show that the students developed their understanding of how chemical knowledge and products are acquired and used. Among 44 knowledge patterns throughout the eight topics, 18 knowledge patterns appeared in more than 60% of the groups' lab reports. We believe that this finding shows the benefits of the process-oriented curriculum, which provided students the authentic inquiry experience of what chemists do in constructing chemistry knowledge. Students developed a better understanding of chemistry processes through their personal experience of doing science, in which they practiced various process skills. For example, after completing Experiment 2, most groups identified that repeated testing/verification is necessary to minimize the possibility of error (80%), and variables should be controlled to get uniform outcomes for comparison purposes (80%). The students actually observed that they reduced errors by repeating tests and verifying results that had been collected already by other groups. They also observed that they got different results even if they used the same chemicals, since they did not control all the variables. By experiencing various process skills provided by the curriculum, the students seemed to develop their understanding of chemistry processes (i.e., what chemists do to construct chemistry knowledge and what skills are required in the process of knowledge construction). The following description, again from a student's reflection on course experience, shows her perception about the experience of doing science.

> In high school you just did what the teacher said and got your grade, but in here we had to figure it out ourselves. We had to put into action all the skills we learned about observation, collection, and verification. (Reflection, end of semester, Class 1)

Collaboration and discussion within groups and class were also frequently mentioned in students' reflections as an experience which developed their understanding of chemistry processes.

> I really enjoyed discussing with others in this class because it was very interesting to see how everyone had different ideas and opinions on how to do things. It opened my mind, and allowed me to see that there is not always just one correct answer….By discussing our thoughts and findings; it helped me with understanding and learning more. (Reflection, end of semester, Class 4)

The students perceived that they could learn more by collaborating and they gain different ideas and perspectives during the process of learning. This finding suggests that encouraging collaboration and oral argumentation throughout discussion should be emphasized in the Chemistry laboratory curriculum.

The various and detailed knowledge patterns students developed also imply that there are specific types of process skills which are unique or more required for chemistry research, and these skills can be developed through a process-oriented chemistry laboratory curriculum. For example, some knowledge patterns seem to be more essential for a chemistry area, such as synthesizing desired chemical products, separating pure substances from mixtures, and language and symbolism used to classify chemicals and to understand established coding systems for chemicals. This implication supports other researchers' idea that there are specific process skills which are domain-specific, and expertise depends on a collection of schemes specific to domain and content (Friedler, Nachmias, & Linn, 1990; Roth & Roychoudhury, 1993; Rogoff, 1984). Thus, this study provides insights for chemistry laboratory curriculum developers or instructors what types of process skills should be included in the chemistry laboratory curriculum as well as which process skills should be discussed during laboratory classes.

Some knowledge patterns were not developed as well as the others. For example, the knowledge patterns regarding organizing data did not frequently appear in the students' laboratory report. This finding provided us insight on how we might modify our process-oriented laboratory curriculum in the future. The knowledge patterns each group developed also varied, even after conducting the same experiments. This finding implies that laboratory reports including claims, evidence, and reflection can be used as tools to probe or evaluate students' understanding of chemistry processes in a chemistry laboratory setting.

The students' ability to link appropriate and sufficient evidence to their claims, which might be considered their reasoning ability, improved across the experiments. Throughout the semester, the level of evidence the students cited to support their claims regarding chemistry processes tended to improve. While much research has shown the relationship between science process skills and formal reasoning ability (Padilla et al., 1983; Tobin & Capie, 1982), the findings of this study imply a relationship between students' understanding of science process skills and their reasoning ability which connects evidence to claims. Many previous studies have also reported that students often have difficulty in selecting evidence and using it to support their claims (Keys, 1999; Sandoval & Milwood, 2005). This study's findings suggest that process-oriented laboratory activities could improve students' ability to select and use higher level evidence to support their claims.

The criteria we developed to evaluate the level of evidence could be used in other laboratory settings to evaluate students' written arguments. The framework of past studies that were developed to evaluate student arguments in the context of using socio-scientific issues or oral argumentation may not be appropriate for analyzing students' written arguments in the laboratory setting. The framework of this study provides explicit guidelines to evaluate the quality of evidence provided in a written form.

Developing an innovative introductory chemistry laboratory curriculum is one of the main concerns of chemistry education. We believe that the findings of this study have implications for chemistry educators who wish to design or revise an introductory chemistry laboratory curriculum. Though we did not include the data in this paper, we found a tendency of knowledge patterns developed toward the beginning of the semester continuously appeared in later experiments. Future studies could investigate how to modify the curriculum so that students can apply their improved understanding to other experiments.

REFERENCES

Anderson, R.D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education, 13*, 1-12.

Barbosa, P., & Alexandra, L. (2004). *Science inquiry in the CORI framework*. In J.T. Guthrie, A. Wigfield, & K.C. Perencevich (Eds.), Motivating reading comprehension: Concept-oriented instruction (pp. 113-141). Mahwah, NJ: Erlbaum.

Brotherton, P.N., & Preece, P.F.W. (1996). Teaching science process skills. *International Journal of Science Education, 18*, 65-74.

Burns, J.C., Okey, J.R., & Wise, K.C. (1985). Development of an integrated process skill test: TIPSII. *Journal of Research in Science Teaching, 22,* 169-177.

Choi, A., Hand, B., & Greenbowe, T. (2013). Students' Written Arguments in General Chemistry Laboratory Investigations. *Research in Science Education,* 43(5), 1763-1783.

Dillashaw, F.G., & Okey, J.R. (1980). Test of the integrated science process skills for secondary science students. *Science Education, 64*, 601-608.

Feyzioglu, B., Demirdag, B., Akyildiz, M., & Altun, E. (2012). Developing a science process skills test for secondary students: validity and reliability study. *Educational Sciences: Theory and Practice*, 12 (3), 1899-1906.

Friedler, Y., Nachmias, R., & Linn, M.C. (1990). Learning scientific reasoning skills in microcomputer-based laboratories. *Journal of Research in Science Teaching, 27*, 173-191.

Funk, J.H., Okey, J.L., Fiel, R.L., Jaus, J.H., & Sprague, C.S. (1979). *Learning science process skills*. Dubuque, IA: Kendall/Hunt.

Glaser, B.G., & Strauss, A.L. (1967). *Discovery of grounded theory*. Mill Valley, CA: Sociology Press.

Goh, N.K., Toh, K.A., & Chia, L.S. (1989). Use of modified laboratory instruction for improving science process skills acquisition. *Journal of Chemical Education, 66,* 430-432.

Katchevich, D., Hofstein, A., & Mamlok-Naaman, R. (2013). Argumentation in the Chemistry Laboratory: Inquiry and Confirmatory Experiments. *Research in Science Education, 43*, 317-345.

Keys, C.W. (1999). Language as an indicator of meaning generation: An analysis of middle school students' written discourse about scientific investigations. *Journal of Research in Science Teaching, 36*, 1044-1061.

Martin, D. J. (2006). *Elementary Science Methods: A Constructivist Approach;* Thomson-Wadsworth: Belmont, CA.

Merriam, S. (1998). *Qualitative research and case study applications in education* (2nd ed.). San Francisco: Sage.

National Research Council. (1996). *The national science education standards*. Washington, D.C.: National Academy Press.

National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* Washington, DC: The National Academies Press.

Osborne, J.F., Erduran, S., & Simon, S. (2004). Enhancing the Quality of Argumentation in School Science. *Journal of Research in Science Teaching, 41*, 994-1020.

Oloruntegbe, K.O. (2010). Approaches to the assessment of science process skills: A reconceptualist view and option. *Journal of College Teaching and Lerning, 7*(6), 11-18.

Padilla, M.J., Okey, J.R., & Dillashaw, F.G. (1983). The relationship between science process skill and formal thinking abilities. *Journal of Research in Science Teaching, 20*, 239-246.

Padilla, M.J., Okey, J.R., & Garrard, K. (1984). The effects of instruction on integrated science process skill achievement. *Journal of Research in Science Teaching, 21*, 277-287.

Rogoff, B. (1984). Introduction: Thinking and learning in social context. In B. Rogoff & Lave (Eds.), *Everyday cognition: Its development in social context* (pp. 1-8). Cambridge, MA: Harvard University Press.

Roth, W., & Roychoudhury, A. (1993). The development of science process skills in authentic contexts. *Journal of Research in Science Teaching, 30,* 127-152.

Sampson, V., & Gleim, L. (2009). Argument-driven inquiry to promote the understanding of important concepts & practices in biology. *The American Biology Teacher, 71*, 465- 472.

Sandoval, W.A., & Millwood. K.A. (2005) The quality of students' use of evidence in written scientific explanation. *Cognition and Instruction*, *23*, 23-55.

Sharmann, L. (1989). Developmental influences of science process skill instruction. *Journal of Research in Science Teaching, 26,* 715-726.

Simon, H. A. (1981). *The science of the artificial* (2nd ed.). Cambridge, MA: MIT Press. Strauss, A., & Corbin, J. (1990). Open coding. In A. Strauss & J. Corbin (Eds.), *Basics of qualitative research: Grounded theory procedures and techniques* (2nd ed.) (pp. 101-121). Thousand Oaks, CA: Sage.

Tobin, K.G., & Capie, W. (1982). Relationship between formal thinking ability, locus of control, academic engagement and integrated science process skills achievement. *Journal of Research in Science Teaching, 19*, 113-121.

Veal, W.R., Taylor, D., & Rogers, A.L. (2009). Using self-reflection to increase science process skills in the general chemistry laboratory. *Journal of Chemical Education, 86*, 393-398.

Walker, J.P., & Sampson, V. (2013). Learning to argue and arguing to learn: Argument-driven inquiry as a way to help undergraduate chemistry students learn how to construct arguments and engage in argumentation during a laboratory course. *Journal of Research in Science Teaching, 50*, 561-596.

Wellington, J., & Osborne, J. (2001). *Language and literacy in science education*. Philadelphia, PA: Open Press.

Yeany, R.H., Yap, K.C., & Padilla, M.J. (1986). Analyzing hierarchical relationships among modes of cognitive reasoning and integrated science process skills. *Journal of Research in Science Teaching, 23*, 277-291.

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