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Development of the Scientific Inquiry Process Model Based on Scientists' Practical Work

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Abstract: The purpose of this study was to develop a scientific inquiry model that makes scientific inquiry accessible to science teachers as well as students. To develop a scientific inquiry model, we investigated the research process demonstrated by ten scientists who were working at academic research institutions or industrial research institutions. We collected data through scientists' journal articles, lab meetings and seminars, and observation of their inquiry process. After we analyzed the scientists' inquiry strategies and processes of inquiry, we finally developed the Scientist's Methodology of Investigation Process model named SMIP. The SMIP model consists of four domains, 15 stages, and link questions, such as “if, why”, and “how”. The SMIP model stressed that inquiry process is a selective process rather than a linear or a circular process. Overall, these findings can have implication science educators in their attempt to design instruction to improve the scientific inquiry process.

Key words: Scientific inquiry model, Inquiry process, Inquiry of scientist, Procedural strategy

I. Introduction

Inquiry is the central component of science learning (Grandy & Duschl, 2007; Martin-Hansen, 2002; Colburn, 2000; Lederman, 1998; White & Frederiksen, 1998; Lunetta, 1997; Roth, 1995), and it is a term that is used often but with multiple meanings. Inquiry-oriented science instruction has been characterized in a variety of ways over the years (Deboer, 1991; Collins, 1986; Rakow, 1986) and it has been promoted from a variety of perspectives. Some have emphasized the active nature of student involvement, associating inquiry with “hands-on” learning and experimental or activity-based instruction. Others have linked inquiry with a discovery approach or with a development of process skills associated with “the scientific method”. The National Science Education Standards [NSES] (1996) described inquiry as a step beyond science as a process, in which students learn skills such as observation, inference, and experimentation. This new vision includes the processes of science and requires that students combine processes and scientific knowledge as they use scientific reasoning and critical thinking to develop their understanding of science. The Standards (1996) emphasized inquiry as followings: 1) it is central to science learning, 2) it includes interrelated processes of science such as observation and inference, 3) it involves questioning and constructing explanations, 4) it involves testing explanations against existing science knowledge via experimentation, 5) it incorporates communication of findings, 6) it involves critical thinking by looking at alternative possibilities, and 7) it comprises behaviors such as meeting challenges and acknowledging limitations. A review of the literature stresses inquiry approach in science teaching so that our students learn science in a more authentic manner and obtain efficient strategies for acquiring, transforming, organizing, storing, and using information useful in problem solving (Gilmer & Alli, 1998; Roth *et al.*, 1998; Spiegel, 1997; Roth, 1996; Nersessian, 1995; Schank *et al.*, 1994; Bruner, 1961). These approaches assume that students need opportunities to find solutions to real problems by asking and refining questions, designing and conducting investigations, gathering and analyzing information and data, making interpretations, drawing conclusions, and reporting findings. Although these various concepts are inter-

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related, inquiry-oriented instructions were not synonymous with any of them (Haury, 1993).

Helping students to develop adequate conceptions of the nature of science, scientific inquiry has been a continual objective in science education (National Research Council [NRC], 1996; American Association for the Advancement of Science [AAAS], 1989, 1993; National Science Teachers Association [NSTA], 1982; Klopfer, 1969). This objective has been agreed upon by most scientists and science educators for the past 10 decades (Lederman, 1992; Kimball, 1967-1968; Central Association of Science and Mathematics Teachers, 1907). Presently, there is a strong agreement among the major reform efforts in science education about the importance of enhancing students' scientific inquiry despite their varying pedagogical or curricular emphases (NRC, 1996; AAAS, 1990, 1993). Students should learn scientific knowledge in a classroom, but this learning scientific knowledge of itself is insufficient. They should "learn how to make scientific knowledge". Students should develop an awareness of their inquiry process, thus their ability to reflect on inquiry process could enable students to improve their learning expertise as well as acquiring subject matter expertise. A focus on developing such learning and inquiry expertise is missing in most school curricula (Lederman, 1998; White & Frederiksen, 1998).

A question for science teacher educators is how to prepare teachers who can facilitate inquiry in their classrooms. Several sources of information about the nature and practice of inquiry-based teaching are available (Shwartz *et al.,* 2005; Spiegel, 1997; NRC, 1996; AAAS, 1989, 1993). However, Loucks-Horsely (1997) holds that teachers will find it difficult to use inquiry-based methodologies if they themselves have never experienced inquiry-based methodologies. Krajcik *et al.* (1998) maintained that middle school students were thoughtful in designing investigations and in planning procedures, but they had weak areas such as generating their focus on the scientific merit of questions, systematically collecting and analyzing data and drawing conclusions. One of the main reasons why students have difficulty in generating questions is that teachers do not provide students with opportunity for them to generate questions; instead, teachers themselves make an attempt to connect observing and generating questions. It is noteworthy that, contrary to common belief, science never starts with observations (Chalmers, 1982). Observations and investigations are always motivated and guided by, and it acquires meaning in reference to questions or problems (Lederman, 1998).

Recently, science education investigators have used many different approaches to understand scientific problem-solving. Science teachers vary considerably in how they attempt to engage students in the active search for knowledge. Each of these approaches has brought forth a vast amount of models and theories, regarding basic processes involved in an inquiry process (Harwood, 2004a; Robinson, 2004; Bruce & Bishop, 2002; Reiff *et al.,* 2002; Sorenson-Johnson, 2001; Krajcik *et al.,* 1998; White & Frederiksen, 1998). Most of the writing in the 1960s (i.e. Schwab, 1962; Taylor, 1962) emphasized an earlier portrayal of the scientific method as a five- or a six-step process that leads directly to the conclusion of science problems (Reiff *et al.,* 2002). These steps include: 1) defining problem, 2) constructing hypotheses, 3) experimenting, 4) compiling results, and 5) drawing conclusions (National Society for the Study of Education, 1947). These steps, outlined in the first half of the 20th century, persist in modern science textbooks. A focus on inquiry always involves thought, collection, and interpretation of information in response to wondering and exploring. Finley & Pocovi (2000) identify six steps to the scientific method as: 1) recognize and research the problem, 2) form a hypothesis, 3) conduct an experiment in which control variables to test the hypothesis, 4) collect, organize, and analyze all relevant data, 5) form conclusions, and 6) present a theory. Yet the traditional problem-solving models are often inadequate for building up in the students' diverse and personal backgrounds. These models are too simple a stepwise and linear process to develop students' recognition for the nature of science. Moreover, these models are helpless for the collaborative inquiry and reflective practice that people need as they engage with others in their roles as productive members of a group. Whereas traditional science inquiry education can be viewed as the acquisition of concepts and terminology, inquiry reforms emphasize the need for students to perform tasks similar to those encountered in scientific practice: posing questions, generating and interpreting data, and developing conclusions based on their investigation (Linn *et al.,* 1994). Developing deep understandings of the nature of scientific explanations, models, and theories as well as the practices are used to generate these products. At these points of view, scientific inquiry models should be based on scientists' approach methods or problem-solving strategies, but developed models up to this day have a little consideration about scientists' practical works.

Although inquiry is an essential component of science learning, we know little about scientists' research processes in regular scientific situations (Lederman, 1998; McComas, 1996; Bauer, 1992). Because the scientists' research process is a desirable model of the problem-solving process, we investigated that the research process of the scientists' inquiry makes a desirable research model for the science classroom. Most inquiry process models are based on scientists' beliefs of the inquiry process or the students' desire of the inquiry process (Harwood, 2004b; Krajcik *et al.,* 1998; White & Frederiksen, 1995), but scientists do not actually conduct their research inquiries as they believe (Reiff *et al.,* 2002). Science educators should call to mind Novak's (1964) suggestion about inquiry: "Inquiry is the set of behaviors involved in the struggle of human beings for reasonable explanations of phenomena about which they are curious". Therefore, inquiry involves both activities and skills, but the focus is on the active searching for knowledge or understanding to satisfy a curiosity.

We report findings from case studies of scientists as they carry out their own investigations. Therefore, we developed models based on scientists' practical works. We furthered how scientists made questions, hypothesized, designed investigations, carried out examinations, made conclusions, and reflected their outputs.

II. Methodology and Data Collection

1. Participants

To analyze the scientists' inquiry process, we interviewed ten scientists who were working at academic research institutions or industrial research institutions. Table 1 informed the participated scientists, their fields of investigation, and their sources of analysis. The scientists have contributed to journals cited in SCI (Scientific Citation Index) in over five papers over the last five years.

Table 1

Participated scientists, their investigation fields and analysis data source

Scientist	Investigation field	Analysis data source
A	Molecular biology	Interview, Lab note, Observation, Journal paper, Lab meeting
B	Genetics	Interview, Journal paper
C	Ethology	Interview, Journal paper
D	Ethology	Interview, Journal paper
E	Ethology	Interview, Journal paper
F	Electronic physics	Interview, Journal paper
G	Atmosphere science	Interview, Journal paper
H	Ceramics science	Interview, Journal paper, Lab note
I	Astronomy	Interview, Journal paper, Observation
J	Inorganic chemistry	Interview, Journal paper

2. Data Collection with Tools

We viewed the scientist as an inquirer who was investigating problems in scientific situations. To find out about the inquiry process, we used three different methods. The first method was to review each scientist's journal articles and lab notes. The second method was to interview each scientists' personal inquiry history based on their practical works. The last method was to observe laboratory meetings or seminars.

The first research method was practicable in analyzing historical accounts of scientific discoveries to uncover the mechanisms involved in scientific reasoning. Nersessian (1992) and others (Gooding, 1992; Holmes, 1985; Tweney, 1985) have conducted details of diaries and notebooks that made it possible to infer some of the cognitive processes involved in particular scientific discovery. This approach has yielded rich and important accounts of some cognitive components of a particular discovery. However, this method has its drawbacks. The main limitation is that only indirect and selective access to the cognitive processes underlying scientists' discoveries can be obtained (Dunbar, 1995). Journal articles and lab notes were used to gather information about each scientist's current matter of concern. We were able to collect background information on their research projects, the rationale for conducting their research and about their interests, hypothesis, experiment methods, and investigation results, etc. However, some of the information was not exposed in journal articles or lab notes because the scientists have been involved in a variety of science departments. Based on this information, we designed a semi-structured interview protocol.

The second research method was appropriate for gathering information and having direct bearing on the research objectives. Scientists were used to follow up unexpected results or to go deeper into the motivations of respondents and their reasons for responding as they do (Kerlinger, 1970). Therefore, we used the interviewing method in conjunction with reviewing to make up for each other. Interviews with ten scientists were conducted using a semi-structured interview protocol (Appendix 1) designed to probe subjects' inquiry process. Interviews were video/ audio tape-recorded, and the interviewers took field notes during the interview. In addition, the transcripts and field notes represent our data. As part of the investigation into scientists' scientific inquiry process, scientists would often describe how they performed the science.

The last research method was appropriate to analyze what scientists think and to explain the reasons at that point in time (Dunbar & Blanchette, 2001). We think that the observing the inquiry of scientist provided us with several important implications. It served us information concerning scientific inquiry process, stepwise selection, strategies when scientist met the problematic situation, and their reflections. However, we could not observe the whole procedure or account thick description because we did not have sufficient knowledge about each scientists' investigation field.

To collect more information, we recorded lab meeting situations. Lab meetings or seminars was adequate to analyze scientists' inquiry strategies because researchers communicated with each other, reflected on their outputs, compared with other researchers' results, and determined their research directions at lab meetings or seminar situations.

3. Data Analysis

(1) Transcription

All information and collected data (i.e., audio/ video tapes, lab notes, journal articles including drafts of papers with comments, and other relevant materials) were transcribed and coded. Transcriptions were made with five independent transcribers with a relevant background in the interviewed scientists' research fields.

(2) Develop coding scheme

After transcription, we developed a coding scheme for the elements of the scientists' inquiry process. First, we compared six inquiry process models one another (Harwood, 2004a; Bruce & Bishop, 2002; Reiff *et al.,* 2002; Sorenson- Johnson, 2001; Krajcik *et al.,* 1998; White & Frederiksen, 1998) to derive inquiry process elements. To improve the reliability, the coding scheme was made by three independent science education researchers who were experienced in making coding schemes. Each of the developers analyzed transcripts and created codes using their own opinions. After the analyses of the transcripts were completed, developers integrated the whole coding schemes through comparison and modification until the conformity of researchers came to 0.8. The incipient version of the derived coding scheme consisted of three domains and thirteen stages. About twelve discussions were achieved during three months to modify the coding scheme. The final version of the derived coding scheme was made up of four domains and fifteen stages (Appendix 2).

(3) Coding

Using developed coding scheme, we analyzed, sentence by sentence, the process of inquiry and strategies that the scientists conducted. Following the transcription, data was coded by a set of categories derived from the developed coding scheme.

(4) Four phases in analyzing data

Data was analyzed in several phases. First, we analyzed each scientist's inquiry field for the inquiry process by analyzing lab note and interview protocols. Transcripts included a description of what scientist did and what they thought. The transcriptions were coded under different categories such as 1) the process from questioning to hypothesizing, 2) the process of designing an experiment, 3) the process of collecting data to analyzing data, and 4) the process of evaluating the output. In addition, we noted the reasons why scientists thought/acted like they did during an inquiry procedure. The second phase of analysis involved comparisons across the cases of select strategies classified by inquiry fields. We guessed that each scientist had particular characteristics, so scientists would select different inquiry methods to design experiments. We compared inquiry processes and selective strategies, case by case, with one another. The third phase of analysis involved unexpected problems occur in various situations during the process of inquiry. These types of questions assumed the forms of "if, why", and "how". We analyzed when the questioning occurred and which questions were represented.

III. Results

We analyzed our data with two points. The first point of view was the configuration of inquiry process of scientists' practical works. We studied the process of each scientist and found the characteristics which appeared during the scientists' investigation. The second point of view was the configuration of strategies which was used in practical works. Based on these points, we made the inquiry process models and described the characteristics of the model in discussion part.

1. Inquiry process of scientists' practical work

(1) Starting point of the investigation

Knowing the consequence that each of the scientists was engaged in a variety of investigation fields, they conducted their investigation with various methods appropriate to the specific situations. Scientists B, E, G, H, and J began the investigation after collecting data, scientists A, C, D, and I began it after observing phenomenon, and physicist F began it after analyzing data, and so on. Furthermore, the recognitions of starting point of investigation were distinct difference among scientists.

Scientists investigated the known data or the known results which were made by another researchers when engaged in scientific problem situation. To hypothesize and to design the experiment, scientist investigated the known data and methodologies appropriate to his investigation if necessary. In the Case 1 and 2, scientists observed the phenomenon and made a causal question "why". The causal question was made from the observation by the scientists before they made the hypothesis or prediction.

A scientist from ethology explained the history of inquiry from observation to design an experiment as:

> Case 1.
> "··· then until I observed that situation, I didn't know about xerontophagy. I didn't know there was a young who eat their mother spider. The young whom I observed didn't act like that. ···(ellipsis)···. But after observing this situation, I tried to search, and I guessed it was not xerontophagy. So it was necessary to certify this phenomenon was not in accord with xerontophagy. And an operative experiment was necessary to certify this phenomenon···" (Scientist D, 2006. 2)

After collecting data to design an experiment, another scientist from an inorganic chemistry explained the history of inquiry as follows:

> Case 2.
> "...to know the effects of this chemical compound, we had to compose a compound..... the compound that has been known well. However, the effects of the compound was not reported when some kinds of ligand and position were exchanged. Despite this fact, I started to investigate the effects of this compound because I was convinced the better effects of the compound when ligands were exchanged based on theoretical computation...." (Scientist J, 2005. 2)

According to Case 1, the scientist observed the unexpected phenomenon which he had not experienced yet. He made a question from an abnormal situation and searched related references with this phenomenon. After he had generated a hypothesis, he designed the experiment. In this case, scientist made a causal question: "why do the young spiders eat their mother spider?" Causal question "why" was used as the key question to make the hypothesis. And then he designed the experiment to certify his own hypothesis. This approaching method can be recognized as the general process of inquiry. In Case 2, the scientist started the investigation with his conviction based on theoretical computation. The key question "why" appeared before making the hypothesis. To know the question "why this chemicals reacted like that", he searched the known data to compare with his own prediction, and he calculated the effects of the compound by computational simulation. Then, he was convinced of the positive effects of his chemical compound.

The next case shows a molecular biology scientist's conduct of searching the known knowledge.

> Case 3.
>
> "··· We searched the references connected with a theme and investigated the results that were concluded by other researchers. Then, we experimented with cell walls because transgenics were developed. In other words, it was recognized that sebum in melon, but we observed that some sebum in melon. Therefore, we made transgenic targets in the first and the second sebum···" (Scientist A, 2006. 2)

Scientist A from the quotation in the above observed that the sebum in melon and compared with another's research result. Then, she attempted to design an experiment. She skipped generating a hypothesis because experiment began with the assumption that sebum existed in melon. Usually generating hypothesis was recognized as a precedent step of designing experiment, but it could be left out in this situation.

(2) Hypothesizing and designing

Hypothesizing induced the experiment based on scientists' predictions. After observing the phenomena, scientists made some questions and hypothesis. Then, they started the research experiment to verify the hypothesis. Sometimes scientist predicted the result of experiment even if the result did not tally with the hypothesis. Scientists made the methodological question "how". "How" is the key question to design the experiment or the whole investigation. After hypothesizing, methodological question led the design of experiment.

Subsequently, scientists conducted the experiment to verify the hypothesis or the prediction. They prepared an appropriate framework, operating machines, tools, samples, and so on. Here, we need to pay attention at these processes in which scientists' know-how are used in designing the experiment. Scientists' know-how about their inquiry came out through the whole process of investigation: observing, measuring, searching the known data or materials, hypothesizing, and designing an experiment, and so on. The most salient know-how of these processes is designing an experiment.

Case 4 and Case 5 show two types of experiment that scientists conducted.

> Case 4.
>
> "We made the hypothesis, but we couldn't predict the effects of the compound authentically. There were some possibilties that negative results could be appeared. However, in my case I was lucky to derive the positive effects that were previously predicted as positive... (ellipsis)... We composed the compound by using the methods that high degree of purity was yielded. When reaction gave dissatisfaction, we repeated a large number of experiments to find out the optimum conditions....(ellipsis)... because each of the laboratories had different condition. Then reiterative experiment was needed to find out the optimum conditions that were fitted in the laboratory." (Scientist J, 2005. 2)

According to Case 4, the scientist conducted a number of pre-tests to find out the optimum conditions and to design the experiment. He hypothesized the effects of the compound, but he couldn't predict that the result would be positive or negative. Therefore, he conducted the experiment until he could find out the appropriate conditions.

> Case 5.
>
> "There must have been a cooperation, with my confidence, and some reactions. However, I could not say that it was a cooperative prey capture behavior without a visual evidence. I had to describe with the data such as frequency of a behavior, errors, and so on. Sometimes pre-test was

> unnecessary, but we needed to pre-test to describe some evidence, and we conducted the pre-test to design the experiment more exquisitely. We couldn't waste the samples because these samples were rare in wild state of nature. Through the pre-test, some samples were sacrificed to find out the appropriate group size and the sample size that led the appropriate standard deviation." (Scientist B, 2006. 2)

Case 5 shows that the scientist carried out the pre-test with some samples. To design a main experiment more exquisitely, he conducted the pre-test and collected sample data. In Case 5, he conducted the pre-test with confidence, different from the case 4, and he needed some evidence to show with limited samples. Consequently, two cases described the pre-test as an overhead operation to design the experiment.

We also observed scientist A's inquiry process from designing experiment to conducting pre-experiment. On the first day we observed, she conducted pre-experiment five times, searched the experimental journal data, and selected appropriate samples to design experiment, to find optimum conditions, and to compare the characteristics one another. The bases of the sample selection were the results of experimental journal data, which she searched, and lab meeting discussion with co-workers. However, she needed additional experimental data because the characteristics of samples to experiment were not perfectly appropriate for her inquiry demanded. From second day to third day, she conducted additional experiments to find out additional characteristics of the samples and the optimum condition. She explained that these additional experiments were necessary to increase the accuracy of hypothesis and main experiment which means scientist must have abundant knowledge or know-how to find out and to solve the problem. We observed that she made six questions during these procedures. Two questions were causal, three were methodical, and one was predictive question. These questions were induced from unexpected observation and anomalous data. To settle the problem, she searched journals which were related to her data, or she took a co-worker's advice. For the most part, questions were solved with these approaches (excerpted from scientist A's daily journal writing, 5/12-17/2005).

The next cases show the scientists' know-how of designing an experiment.

> Case 6.
> "And then, we looked the signal by using transmission right. Generally, the absorption signal was too weak when we observed the signal by this method. We had known how to amplify the absorption signal, so we attempted an experiment to amplify the signal. Then, the absorption was stronger when we added another laser at the same time." (Scientist F, 2005. 2)

In Case 6, the scientist had known the method how to amplify the signal, so he could solve the problem when the absorption signal was too weak to detect.

> Case 7.
> "There was someone who conducted the investigation that was similar to our subject, and he did better than we did. We invited him to our seminar to demonstrate the capability and result of our investigation and to let him offer his seminar... Then we could take his advice about our investigation, and we also suggested him to co-work with our laboratory because he had an ability to solve our problems." (Scientist J. 2005. 2)

In addition, Case 7 shows how to solve the problem when the scientist could not solve the problem or needed some advice from an advanced investigator. Like these cases, scientists knew how to solve the problems when they met a routine problem. Sometimes, scientists solved the problem by using their own know-how, but they requested other scientists' know-how when they could not solve the problem by their own ability.

(3) Conducting experiment and analyzing data

Carrying out the experiment is following process of designing an experiment. Scientists carried out the experiment according to their experimental designs to verify the hypothesis. To carry out the experiment, scientists set up the experiment adequately and put into an action. The same experiment was conducted several times to collect a reliable data and to redesign the experiment when anomalous data or unexpected data were derived. Experimentation to certify the hypothesis could make derivative processes such as new hypothesis or alternative hypothesis.

Case 8 shows the appearance of carrying out an experiment process.

> Case 8.
>
> "First experiment was to test a male salamander's moving behavior when one female and three male salamanders stay at one site and one female salamander stays at another site. After the experiment, the ratio of moving to one female salamander site was higher than another. It was an evidence that male salamander could distinguish difference between two sites. After all, a different experiment was tested to find out a male salamander's behavior when three male salamanders stay at one site and nothing stays in another site. At this time, a male salamander moved to the site of three salamanders, not the empty site ... (ellipses) ... a male salamander moves to the site to search food ... (ellipses)... The next presumption was, if salamanders were in a breeding season, the possibility of finding female salamanders goes high where male salamanders were founded. However, this presumption was not tested yet... (ellipsis) ... The reason why I selected the latter was that I thought about the existence of repelling pheromone. This pheromone spurns the same distinction of sex, instead of temptation. Some insect has this pheromone. That is the reason why we do not know about this even now." (Scientist C, 2005. 2)

A scientist who inquires into the salamander's moving behavior experimented to verify his hypothesis that a male salamander interacts with another male salamander. The first experiment showed that the male salamander moved to the site where was free from male salamanders, and the second experiment showed that the male salamander moved to the site where other male salamanders existed. This anomalous data made the scientist confused. In this process, he tested his hypothesis by experimentation, but anomalous data or unexpected result made him to formulate alternative hypothesis or alternative experimental method. In Case 8, scientist tests the second experiment to certify the first experiment, but the result of the second experiment showed the anomalous data. He searched the reason why this data came out, and then he described some alternative hypotheses such as searching the food, probability of discovery of female salamander and repelling pheromone.

The next example of lab meeting observation shows the processes of conducting experiment and analyzing data of scientist A. From May 24th to 29th, she analyzed the output data and conducted the additional verification process. She accepted not only expected data, but also anomalous data. Then using the known data and co-workers' advice, she made an effort to find out the reasons of anomalous data. In this process, she made four additional questions which made her to advance other research project. As this example shows, analyzing and verifying process makes a scientist more delicate and reflective (excerpted from scientist A's daily journal writing, 5/22-29/2005).

In this process, we should look for the important fact that scientist searched the known knowledge during the process of analyzing data as well as process of hypothesizing. Investigating the known data or requesting an advice came out from the inquiry process, and this process was linked to the problem solving situation and comparing the scientist's own result with other's result.

(4) Evaluating the result

After collecting the data, scientists analyzed the result and compared it with their hypothesis. The scientists reflected on their findings through this process; analyze the result, compare with hypothesis, communicate with others, and compare with others' result, and so on. Cases 9 and 10 show the scientists' evaluating process during the whole investigation.

> Case 9.
>
> "So we conducted lots of same experiments after formulating hypothesis, but the results rejected the hypothesis. However, I was deeply attached to some intuition when I made the hypothesis and conducted from experiments. And I thought the result was wrong. Something was subjectified I had to accept the result or drop the experiment, but I spent my summer season to make the same experiment. I reflected on myself; 'Did I make a mistake at the process of controlling?' 'Perhaps there was something wrong during the experiment.' Trying to find an answer to my question, I made experiments all the time. Then, the same result was outputted. So what could I do? I should have to accept these results but I couldn't." (Scientist B, 2006. 2)

In Case 9, the scientist met contrary evidence to his hypothesis that made him to reject his hypothesis. However, this scientist could not reject his hypothesis

Table 2

Investigation processes of scientists

Scientist	Investigation process
A	Recognize the Phenomenon → Investigate the known → Compare with other's result → Design experiment → Collect data → Analyze data → Result
B	Investigate the known → Generate Hypothesis → Design experiment → Collect data → Compare with hypothesis → Result
C	Recognize the phenomenon →Investigate the known → Generate hypothesis → Design experiment → Collect data → Analyze data → Compare with other's result → Result
D	Recognize the phenomenon → Generate hypothesis → Design experiment → Collect data → Analyze data → Result
E	Investigate the known → Recognize the phenomenon → Compare with other's result → Generate hypothesis → Design
F	Analyze data → Make question → Investigate the known → Compare with other's result → Generate hypothesis →Design experiment → Analyze data → Compare with hypothesis → Result
G	Collect data → Integrate data → Analyze data → Compare with other's result →Reflect on the findings
H	Investigate the known → Analyze the pretest → Design the experiment → Collect data → Analyze data → Communicate with others → Result
I	Recognize the phenomenon → Analyze data → Integrate data → Compare with other's result → Generate hypothesis → Observation (Collect data) → Analyze data → Result
J	Investigate the known → Generate hypothesis → Design the experiment → Collect data → Compare with other's result → Result

easily because he had a strong confidence in his own hypothesis, but he had to recognize the negative result. Until the result was accepted, he doubted his controlling, possibility of subjectivity, and any other mistakes during the experimentation. Case 9 shows that it was hard to change over the hypothesis when he felt confident of the hypothesis.

> Case 10.
>
> "When the result indicate that the hypothesis should be rejected, first of all, I reflected on myself. I consider the connection between variables that I controlled, and the relation among other facts, and so on. Then I searched the papers that other researchers investigated to find the mistake of my investigation. When we searched the others' papers, we must review not the abstract but the discussion or applications of the paper to represent our results." (Scientist I, 2006. 1)

Case 10 is about scientist's reflection. Additional process with Case 9 is searching the others' results and comparing it with his result to find out the mistake of investigation. Thus, scientists evaluate their result and conclusion by reflection. If a scientist accepts the rejection of his hypothesis in the process of the evaluation, he needs to make a new or alternative hypothesis and modify the inquiry method more clearly.

The rough investigation processes of all scientists who participated in this study were described as follows in Table 2.

Table 2 roughly presents a partially connected process of the scientists' investigations, not the whole process of the investigation. In reality, detailed processes are connected with scientist's level of skill, in the context of their working environment. For example, Scientist A brought a wealth of experience to her research subject, so she could have enough knowledge about her research. However, she was dependent from her co-worker's interpretations during the process of analysis data. She determined the direction of investigation through the analysis of the experimental result without hypothesizing. Finally, she confirmed success or failure by comparing experimental result with research subject. In contrast, although Scientist E and Scientist I had sufficient empirical data and experiences, they preferred the direct research and analysis by themselves rather with their co-workers. These two scientists made manifold hypothesis about their questions, and conducted manifold experiments with additional observation and investigation of known knowledge.

Because these three scientists had different charac-

> Problem occurred during analysis:
> an opaque color after Na-tetraborate's input
> → Possibly Na-tetrabotate made it opaque.
> *(5.12.2006., Scientist A's Lab note)*
>
> Researched the paper:
> Na-tetraborate which was kept over one week increased the viscosity.
> → If we use the reagent like this, a chromogenic problem would be happen.
> → We must check the viscosity if the reagent was made before one day.
> *(5.16.2006., Scientist A's Lab note)*
>
> When we made Na-tetraborate reagent:
> → Little affect on chromogenic reaction.
> → Caution! Al foil cap was eroded. Na-tetraborate reacted with H_2SO_4. A gas product was generated and reacted with Al foil.
> *(5.23.2006., Scientist A's Lab note)*

Fig. 1 *Scientist A's problem situation and strategies.*

teristics, different investigation field, and different experiences, they used different methods and strategies during the investigation. Different methods and strategies were needed according to the characteristics of research subject and researcher. Therefore, we could apply these methods and strategies to the specific process rather than whole process. Table 2 released that every scientist has their own characteristic inquiry processes and methods. This result shows that the steps of process were unequal, and the beginning step was multifarious. Because no one model can encapsulate inquiry based processes and range, they encompass with the view of process steps.

2. Scientists' practical strategies for anomaly data/ unexpected results

When scientists were faced with unexpected results or anomalous data, they selected five different strategies as follows: 1) they searched the reason and experimented again, 2) they investigated the known, 3) they contrived alternative experiment, 4) they turned around their thinking, and 5) they dropped the result. The way to evaluate results included comparing them with hypothesis, comparing with other's results, and communicating with others. According to the results of these ways, scientists judged the values of their outputs and evaluated their investigation.

(1) Strategy 1 - searching the reason and experimenting again

The following two instances show the strategies of solving problem through investigating the known knowledge and repeated experimentation.

The lab note example of scientist A (Fig. 1) shows the one strategy of solving problem. The lab note shows the problematic situation when she analyzed the contained quantity of pectin in pepper. The problem was that reactant's color became white as milk when she titrated the sample with Na-tetraborate. She searched for the reason why the reactant became opaque, then she assumed that Na-teteaborate reagent might be controversial. She attempted to variety test with Na-tetraborate, and concluded that this reagent must be used in fresh state. In these problem solving process, she tested another characteristic of Na-tetraborate, which became known as the property of reaction with H_2SO_4.

Case 11 shows the repetition strategy of Scientist J. He met the problem of reproducibility, then he searched the appropriate optimum condition to his laboratory circumstance by repeating experiment.

> Case 11.
> "We experimented according to the known composition methods which were in high degree of purity and yield, but the reaction was not appropriate in laboratory. Then we experimented this reaction twenty or thirty times again to find out an optimum condition." (Scientist J. 2005. 2)

Scientist J tried numerous experiments since he found out an optimum condition and this strategy provided an experimental method how to construct laboratory condition.

(2) Strategy 2 - investigating the known

This strategy was used in the generality of scientists' problem cases. As we described earlier, scientist always searches for known knowledge from journals, advice of experts, and discussion with peers. There is the example of Case 12 below.

> Case 12.
> "...song sparrow resembles savanna sparrow. Although there is a lot of researches about song sparrow, there are only few about savanna sparrow done by four of five researchers. These researchers investigated the geographical mutation, three investigated with micro-standpoint and one investigated with macro-standpoint. Because with micro or macro oriented standpoint research could not solve these problem, I investigate the standpoint of neutrality." (Scientist E, 2005. 8)

Case 12 shows a strategy for solving a problem. He searched for researchers who investigated the same field of his interest target. He investigated others' research results and analyzed their viewpoints to obtain a clue to solve the problem.

(3) Strategy 3 - contriving alternative experiment

In Case 13, a molecular biologist described her inquiry strategy to design an experimental process and said:

> Case 13.
> "···We made a big hypothesis that a cell wall was a direct cause, but there was a distinct limitation to establish an experiment design in detail. Because the cell wall is not organized in one substance, there are many other factors to affect it, in my case. I classified the causes by three factors, and I ramified the first factor to three or four sub-factors···" (Scientist A, 2006. 2)

In this case, the scientist modified to design alternative experiments because she recognized the limitation of designing her experiment. Therefore, she searched for other alternative experimental methods. The inquiry strategy might be described as follows: "generate hypothesis → design the experiment → recognize limitation → modify experiment design → search alternative experiment method."

(4) Strategy 4 - turning around thinking

In Case 14, Scientist C negated the traditional theory of the role of the pheromone, then he changed his prior conception about the pheromone. He proposed the repelling pheromone to explain the behavior of the male salamander. Scientist C selected the strategy of negation about the traditional theory, and he had the way of turning it around.

> Case 14.
> "By chance, we found out that the sexual ratio of the male ssalamander versus female was about 3.8 : 1, roughly 4 : 1. For example, when a male salamander was tracking a female salamander and if there are four male salamanders around the female salamander, the male salamander must judge to go to the female salamander or not. Traditional research about pheromone was the cross interaction between male and female, but we guessed that it was advantageous to a male when interaction was conducted between two males. So we began investigating to figure out which male salamander would recognize the smell of male or not. We wanted to know that the smell of male would have influenced on the behaviors of another male salamander." (Scientist C, 2005. 2)

(5) Strategy 5 - dropping the result

Sometimes scientists drop their result and go back. This strategy was shown at the reflection process such as Case 15. Scientists A compared the result with her hypothesis and decided whether to accept her result or not. We noticed that this strategy was critical because acceptance of the result induced the basis of verifying the hypothesis, alternative thinking and alternative design of the inquiry.

> Case 15.
> "The largest mistake was that we judged it to be connected with the membrane rather than with the cell wall. After gathering experimental data related to membrane, we concluded that it might be a wrong idea. So we dropped the result, and went back to the cell wall." (Scientist A, 2.2006)

Scientists selected a few adequate strategies to solve problems when they encountered unexpected problematic situations. The unexpected situations occurred throughout the inquiry process, and scientists should have chosen a selection or a rejection moreover to go forward or stop the investigation. Cases 8, 9, and 10 show the scientists' strategies in the inquiry processes. In Case 8, the scientist conducted the alternative test to discover male salamander's

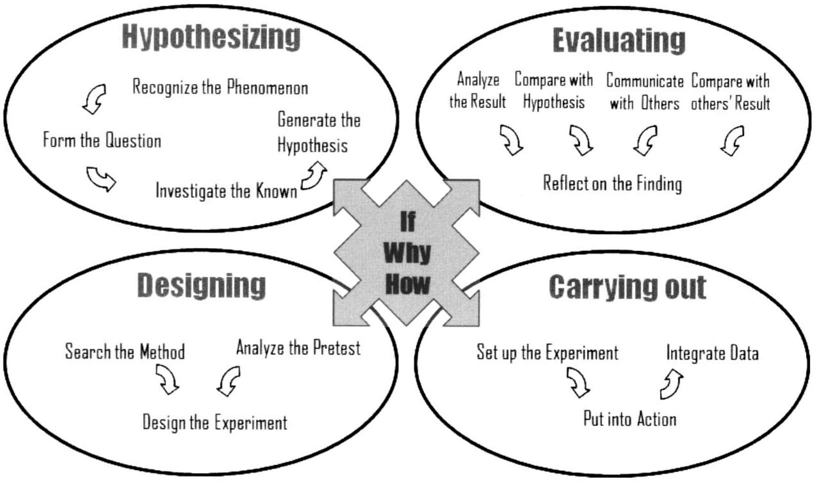

Fig. 2 *The SMIP model.*

unexpected behavior, and he made an alternative hypothesis about the repelling pheromone. Case 9 shows the scientist's repeating experiment strategy to find out the evidence that maintained his hypothesis. In addition, Case 10 describes the reflection when the result which indicated his hypothesis became wrong. Scientists' inquiry strategies are shown appropriate selections to solve the problem and these strategies appeared in the whole process of the inquiry, but they were relying on the scientists' skill and experience which makes scientists select the optimum strategy.

IV. Discussion and Implications

We studied the inquiry process and strategy of scientists. We report findings from case studies of scientists as they carry out their own investigations. In response to these results, we propose the following inquiry process models based on scientists' practical work. The inquiry process model that we made was from the analysis of the collection of scientists' descriptions about how they practiced science.

1. Model of Scientific inquiry process: the SMIP (Scientist's Methodology of Investigation Process) model

From a practical view, scientists' processes of inquiry within the context of methods are nonlinear and noncircular. This has forced us to develop a more sophisticated model of the process of scientific inquiry than the traditional science method previously discussed. SMIP model (Fig. 2) is constructed of four domains: hypothesizing, designing, carrying out, and evaluating. Each of the domains are linked by questions represented as "if, why," and "how". Each of the domains contains process stages like "Recognize the Phenomenon", "Form the question", "Investigate the Known", "Generate the Hypothesis", and so on.

Generally, the traditional inquiry process model follows the regular sequence of questioning→ hypothesizing → collecting data → making a conclusion or observation → questioning → hypothesizing → examinating → evaluating, etc. An observation or a question was recognized as the first step, and the other processes occurred step by step. However, the inquiry processes of scientists we analyzed did not occur in regular sequence, and some did not begin at the observation or the question. Scientists might begin an inquiry investigation at any domain that emerged from our study. Moreover, none of the scientists emphasize the recursive process as an important part of a scientific inquiry process. They used their own inquiry domain-oriented methodology rather than a traditional inquiry process. The SMIP model does not show the repeating steps and the starting point during an investigation. The domains of the SMIP model were linked by different questions such as a predictive question "if", causal question "why", methodical question "how". These questions were exposed at all domains and played an important role as a link between domains.

The domains and stages of the SMIP model are each outlined below. For those domains and stages with equivalent sorts of items in the traditional scientific method, we included a brief comparison between the domain/ stage and the traditional method steps.

(1) Hypothesizing

The hypothesizing domain shows the process of generating the hypothesis. This domain contains four stages such as recognizing the phenomenon, forming the question, investigating the known, and generating the hypothesis. Each of the stages has two sequences. One is "recognizing the phenomenon → forming the question → investigating the known → generating the hypothesis" and the other is "recognizing the phenomenon → forming the question → generating the hypothesis". However, we ignored the latter sequence because the practice of generating the hypothesis without investigating the known stage seems to be influenced by the personal intuition. As a consequence of this process of stages, scientists were able to make an inquiry hypothesis.

Recognizing the phenomenon stage is equated with observing or making an observation in the traditional inquiry process. Observations occur through out the entire inquiry process. Observations are essential in keeping careful record, staying focused, and as a springboard for the development of questions. The reason why we set limits to observation in the recognizing the phenomenon stage is because observation connotes the necessary condition rather than the sufficient condition. Recognizing the phenomenon is used in this stage as a restricted meaning- uncomplicated view about the present situation which was expected or unexpected. Form the question stage may arise from exposed unexpected problematic situations. A scientific question is generated when someone is faced with a novel phenomenon that is impossible to describe with current knowledge (Lawson, 1995). Scientists define a questionnaire based on their observation and their understanding of the phenomenon. Questioning is a natural result of curiosity that leads scientists toward new knowledge and new understanding. At Investigating the known stage, scientists may be unsure if others have found an answer to the question under the investigation. Moreover, there may be an information available that will guide the study to a fruitful conclusion. Scientists gather information related to the question from reading the literature or by talking with experts in the field. Also, talking with experts is one example of communicating with others in the evaluating domain. Investigating the known allows scientists to define the boundary between what is already known and what is unknown about the question. This information gathering stage may result in the investigator gaining an answer to the original question, the question may be modified to address an issue that is not yet known, or the investigation can continue to verify known results. Informed by a deeper understanding of the question, scientists may proceed to the next stage. In some cases of our research, the investigating the known stage was skipped in the hypothesizing domain, but this doesn't mean this stage is skippable. To generate the hypothesis, scientists should know what is known and what is unknown. When this generating the hypothesis stage follows completion of the prior stage, providing material that may take the scientists back to a stage, we have already described to further refine it or change the question. A good understanding of the literature around the question of interest also guides the scientist in developing a preliminary answer to their question. Common forms that these preliminary answers take are a hypothesis or a prediction. This may be either a formal or an informal articulation.

(2) Designing

Based on the expected direction for problem solving, scientists begin planning and designing the investigation. The designing domain encompasses elaboration of the investigation methods. In the search the method stage, scientists use multiple methods or approaches to investigate their hypothesis. The scientist decides which method would be appropriate for the demonstration and then selects implements that would assist in conducting the method for the investigation. The analyzing the pretest stage is to gather evidence and detailed method information. The investigation might take the form of an experiment or a pretest though other designs were also used. In instances of an experiment or a pretest, scientists would control variables and manipulate one variable at a time to study what was causing the question. In other cases, such as discovery research (Lederman, 1998), scientists may make no effort to control the events in a giving setting. However, their choice of tools and setting maybe influenced by their expectation that these would provide useful responses to their question. The designing the experiment stage is a combination of searching the method stage and analyzing the pretest stage. Scientists often rejected the question at this stage, because their methodological capabilities were insufficient to solve the problem. In this case, scientists who rejected the question were to search possible methods or reserve investigation. Sometimes they tried to search another question related to unexpected phenomenon, it is necessary to investigate which strategies influenced them to select the question.

(3) Carrying out

Scientist found the appropriate investigation method, and when they decided the method capable to prove the question, scientists carried out an experiment and collected data. In the setting up experiment stage, scientists constructed necessary apparatus and carried out experiments. During this putting into action stage, most scientists did repetitive experiments, and the number of times experiments performed was influenced by the variety of investigation fields, characteristics of the subject, the condition of apparatus, and so on. Experiments were considered complete after a satisfactory amount of data had been collected. When collected data were insufficient for analysis or discordant with their predictions, scientists worked out the different strategies to determine whether that they would accept these data or drop these data. During the integrating data stage, scientist integrated all data to make results. Data were analyzed by scientists' proper methods.

(4) Evaluating

After data obtained from carrying out the experiment has been integrated, scientists examine what the results mean. Data can take the form of measurements, field notes, observations, output materials, statistical analysis, interactions among variables, surveys, etc., depending on the method chosen to collect data. Regardless, the scientist looks for patterns and connections within the data. During analysis in the result stage, if the data was inconsistent or some error had appeared to have occurred in gathering data, the scientists might decide to repeat some of the previous stages. This might lead the scientists to modifying the method, by refining the question, researching more information about the question, or making additional observation. For some scientists we researched, this stage was where investigation really beginning, after they had analyzed collected data and then found patterns or connections within the data. In comparison with hypothesis stage, scientists compared output with their hypothesis. They made careful judgments about whether their hypothesis would be accepted or rejected. In the communicate with others stage, scientists represent their outputs to other researchers, co-workers, and supervisors, etc. One scientist said, “if information is not shared with others then it may as well not have existed.” This is the opinion expressed in stressing the necessity of communicating findings to both the scientific community and to the public. Scientists stressed the importance of having good communication skills to explain to others their findings in written or oral form. In communicating with others they often generate new questions, new ideas in the process of bringing ideas together and responding to inquiries. In comparison with other's result stage, scientists compared their outputs with other researcher's result. They also compared the output, result, investigation method, analysis method, and conclusion, etc. This is essential in verifying the results for validity and reliability purposes and for career advancement opportunities. Also, the audience for scientific information is the general public. The gap in the public's perceptions of science and how to obtain scientifically valid information concerns some scientists. In reflection on the finding stage, scientists reported that they spent time reflecting on the meaning and implications of their findings at odd hours or locations. At this time, scientists take a step back from the data and make thoughtful connections. In trying to find significance in the data, scientists spent many hours looking for patterns in the data and making connections to the known information. In Harwood *et al* (2005), the most important characteristic of a scientist was the ability to make connections between the data. That is, to be able to focus on the details of an investigation but also to see the larger picture. This is the key modification to the traditional scientific method that is provided by White and Frederiksen (2000).

(5) Questions: if, why, how

As we discussed previously, the domains of the SMIP model were linked by questions in the form of a predictive question "if", causal question "why", methodical question "how". These questions were exposed at all domains and played an important role as a link between domains. Scientists frequently pose questions that are too vague, making them difficult, even impossible, to answer. These questions can often be modified so they are more specific, allowing scientists to design a realistic experiment to answer their question. Scientists used personal experience but prefer to use scientific merit as sources for questions and they sometimes used established methods as criteria for question selection. The SMIP model can be seen to be functionable when these questions are fed into one of the four domains.

The SMIP model presented here is constructed from scientist's practical investigations. Reiff *et al.* (2002) asserted that it is necessary to investigate the scientist's actual research practices. The SMIP model reflected on scientist's practical research processes, but has some limitations in application in the science classroom. First, in spite of the scientific inquiry process being an ideal process of problem solving, students often can't inquire in the way of a scientists' investigation. Science curriculum has been stressing scientific inquiry, but there are few opportunities for inquiry. A number of kindergarten through 12th-grade programs have been developed that stress inquiry. Although evidence indicates that these approaches help students obtain a deeper understanding of science (e.g., Variano & Taylor, 2006; Brown & Campione, 1996), there are few expensive descriptions of how students engage in inquiry, especially during the difficult period of their initial attempts. Metz (1995) presented a strong argument that elementary students are capable of performing investigations and learning from them, even though, due to limited prior knowledge, their investigations will be less sophisticated than those of adolescents and adults. Although the longitudinal findings are promising, others have described problems students have initially when introduced to inquiry-related activities and where they might benefit from instructional support. Scardamalia and Bereiter (1992) found that fifth and sixth graders tended to generate low-level factual questions rather than questions that could extend their understanding of a topic and that the level of questions students asked depended upon their prior knowledge. Moreover, collaboration was hard to establish. Linn (1992) reported that students had problems generalizing ideas from laboratory experiments to their everyday experiences and to other material they were studying. They responded to questions intuitively rather than drawing on scientific principles under study. Second, in spite of the domains and stages in the SMIP model being based on scientists' practical inquiry, to apply this model to students, demands careful consideration. Scientific applications in the classroom usually require combining multiple models originating from different disciplines. The choice of a model is usually guided by the experience of the science teacher. Once models are chosen, science teachers can run the corresponding programs. However, the process of choosing the right models and running the adequate programs is done empirically. Model characteristics are described in several ways, and the experience from a successful model application is not always registered in a written report. Consequently, science teachers have difficulties in model management activities, and more importantly, in taking advantage from a large number of previous experiences. We believe that it is important to describe and represent scientific process models as well as their associated program implementations. Then, it is necessary to develop the corresponding programs to the SMIP model and the SMIP model should to be judged in its application by students.

The results from this study implied the following.

The traditional stereotype of the scientific method as a linear process fails to accurately describe the practical process that scientists use in approaching their scientific inquiry. A key idea for the SMIP model is that the inquiry process is not linear or circular, but selective strategies have grounded some key questions like “why”, “if”, and “how”. Inquiry is not a linear process; aspects of inquiry interact in complex ways (Krajcik *et al.,* 1998). White & Frederiksen (1995) analyzed students' scientific activity; suggesting a model of the scientific inquiry process. Their inquiry cycle includes question, prediction, experiment, model, and application. These conflicting models suggested a common phase of inquiry, but practical scientific works can't be described through a stepwise approach. The result of this study shows that scientists conduct their investigation independent from the standardized process that is stressed in traditional scientific inquiry learning. Considering the purpose of the scientific inquiry instruction, inquiry learning has been attached too much of importance on procedural elements. Then science educators might consider the alternative methodologies that develop inquiry strategy and conduct the inquiry like scientist.

The SMIP model could be the bases of the inquiry instruction programs. We will develop an adequate instruction program for the SMIP model with consideration of the practical nature of inquiry. The merits of the program based on the SMIP model could be;

a) to consider the characteristics of practical inquiry process. The inquiry programs based on linear or circular inquiry model include the risk which make students have stereotypes on and prejudice against the nature of inquiry and problem-solving process. However, we guess that the program based on the SMIP model can make students to understand the practical nature of the inquiry process.

b) to emphasize the students' strategy and then inquiry process become different according to the selection of strategy. Strategic selection was made from the question which was generated in the whole process, and this selection makes the process of inquiry or direction of inquiry different direction. We anticipated that the program based on the SMIP model could makes students to solve the problem with logic which is connected between making question with strategic selection.

Recommendations for appropriate instructional means must await for the findings of future research. Our study indicates that scientists were thoughtful in each process with their knowledge and experience and they made a full use of appropriate strategies to solve problems, and they weighed their own conclusion with co-workers. We believe students are able to do this like scientists. In addition, we need to find ways to capitalize on the enthusiasm students exhibited to enhance interest in science by using this SMIP model. For the actualization of this desire, we investigated the students' ability for the scientific inquiry with different points of view. The traditional view of the students' inquiry was to develop and to promote the ability of inquiry elements and inquiry processes, but it is necessary to understand students' ability pertaining to scientific strategies, contemplative faculty of the problem-solving and conquest of difficulties, etc. These data will give us suggestions to develop appropriate programs to reinforce students' inquiry capabilities.

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Appendix 1: Key questions in the interview protocol

(1) Describe the whole process of inquiry.
(2) What research have you done?
(3) Why did you conduct such experiments or why did you not conduct other types of possible experiments?
(4) Were there any problems that occurred during the experiments?
(5) How did they reflect their outputs

Appendix 2: Coding scheme to analyze scientists' inquiry process

Domain	Stage
Hypothesizing	Recognize the Phenomenon Form the Question. Investigate the Known Generate the Hypothesis
Designing	Search the Method Analyze the Pretest Design the Experiment
Carrying out	Set up the Experiment Put into Action Integrate Data
Evaluating	Analyze the Result Compare with Hypothesis Communicate with Others Compare with others' Result Reflect on the Finding