STUDENTS’ USE OF METACOGNITIVE SKILLS WHILE PROBLEM SOLVING IN HIGH SCHOOL CHEMISTRY

by

Francine Delvecchio

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ABSTRACT

The purpose of this study was to investigate how purposeful metacognitive instruction affected students’ use of metacognitive skills and their abilities to solve complex chemistry problems. The pilot (n = 18 to 26) and study (n = 21) groups were enrolled in separate Ontario Grade 11 university preparation chemistry classes. A quasi-experimental intervention was implemented, using the pilot study as a control. A Metacognitive Framework that outlined metacognitive skills specific to problem solving in chemistry formed the foundation for the intervention. Pre- and post-test self-report questionnaires measuring students’ use of metacognitive skills (MCAI) and the problem solving tasks (i.e., PSTs) were used to measure the impact of the intervention. Data about students’ metacognitive and problem solving processes were also collected for the study group from: (a) think aloud pair problem solving (TAPPS) protocols, (b) an exit interview with the classroom teacher, (c) the students’ lab reports for two design labs, and (d) a survey of students’ use of the Metacognitive Framework.

One way repeated measures ANOVA indicated that the pre- and post-test MCAI scores were not significantly different within and between the pilot and study groups. A comparison of the higher and lower achievement subgroups within the study group revealed that over time, the mean scores on the MCAI increased for the higher achievement group and decreased for the lower achievement group. One-way repeated measures ANOVA revealed that the post-test PST scores were significantly higher than the pre-test scores, and the groups differed significantly from each other with the study
group scoring higher on both scores. While the statistical analyses revealed few differences, the teacher’s exit interview, TAPPS protocols, pre- and post-test lab reports, and student survey of the Metacognitive Framework indicated that the intervention supported students’ abilities to solve complex chemistry problems and use metacognitive skills associated with planning, monitoring, and evaluation.
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CHAPTER 1
INTRODUCTION

High school students face an unpredictable future in which the skills and knowledge they require are constantly changing. This presents an interesting challenge to students and their teachers. Accordingly, a common theme throughout many statements of the purpose of education in the twenty-first century is the need to develop life-long learners. Science education reforms call for educators to shift from a focus on building the knowledge capacity of students to building their thinking capacity (Miri, David, & Uri, 2007). By doing so, educators will move towards the implementation of a learning-to-learn curriculum that will equip learners with the flexible skill sets needed in a rapidly changing world (Cornford, 2002; Csapó, 2007).

Inherent in this model for education is the requirement that learners develop their problem solving skills. Traditional approaches to teaching problem solving involved repetitive drill practice with routine problems (Hatano & Inagaki, 1986). Miri et al. (2007) identified a need for science education to shift towards greater emphasis on developing students’ abilities to solve complex problems. Similarly, Reid and Yang (2002b) recommended that educators incorporate increased opportunities for students to engage in more open-ended problem solving tasks. Through such tasks, students will have the opportunity to develop the flexible expertise needed to solve real world problems (Hatano & Ignaki, 1986).
When students encounter a problem, they are at the threshold of learning. Flavell (1979) noted that this condition stimulates a metacognitive experience for the learner. Skilled problem solvers respond by employing metacognitive skills throughout their problem solving process. These skills include: (a) identifying the goal of the problem, (b) taking time to understand the problem before beginning a solution, (c) finding connections to previous knowledge, (d) showing greater awareness of their conceptual understanding, (e) breaking down the problem into steps, (f) demonstrating flexibility by revising strategies to meet the identified goal, and (g) practicing self-appraisal of their solution as they work through a task (Haidar & Naqabi, 2008; Whimbey & Lochhead, 1986).

Over my twenty years of teaching high school chemistry, I have become keenly interested in the way students approach problem solving. Rewarding classroom moments occur when my students are actively engaged in their learning and energized by the challenge of taking their understanding to an increasingly higher level. Problem solving is central to students’ learning in chemistry. My informal observations of students have revealed that some chemistry students are intimidated by unfamiliar problems that do not specifically prompt them to execute the appropriate routines. I believe that instruction that fosters students’ conscious and deliberate thinking while problem solving will help these students become more proficient at solving unfamiliar problems. Specifically, instruction that explicitly targets the development of students’ metacognitive skills will support the development of their problem solving skills. Hence, my research explores
these links between problem solving and metacognition, with the intention of using complex problem solving tasks as a means to investigate metacognitive skills in high school chemistry students. My research derives from my perspectives as a practitioner who seeks to find ways to better support students’ learning in chemistry. Given the value of problem solving approaches to learning, I am interested in finding ways to improve students’ abilities to successfully meet the problem solving challenges that are found in the science classroom.

**Purpose**

I believe it is possible to link students’ employment of metacognitive skills with their problem solving abilities in chemistry. The purpose of this study is to explore students’ use of metacognitive skills during problem solving activities and to determine how explicit metacognitive instruction affects their use of metacognitive skills and their problem solving abilities. Four questions guide this study:

1) What is the effect of purposeful metacognitive instruction on students’ use of metacognitive skills?

2) What is the effect of purposeful metacognitive instruction on students’ abilities to solve chemistry problems?

3) What metacognitive skills do students use while problem solving?

4) Can the Metacognitive Framework provide a useful model for problem solving?
Definition of Terms

Problem

A problem is a task that requires the student to implement a strategy to find a solution. These tasks may be described on a continuum from being well-defined to ill-defined (Hollingworth & McLoughlin, 2005). Well-defined tasks require the student to execute a familiar routine or formula. As the nature of the task becomes more complex, the student’s familiarity with an approach to solving the problem decreases. In the case of an open-ended task, the student must define all aspects of the task beginning with the goal, and progressing through the design of the solution. The outcome for such a task is one of many possible solutions. In this study, I focused on problems that present the student with a goal and the necessary data. However, initially, the method for solving the problem was unknown to the learner. I describe these tasks as complex problems.

Problem Solving

Problem solving is the process by which a student arrives at a solution to a problem. Integral to this are students’ thinking, planning, reasoning, and executing of the plan as they progress from the initial problem state to the fulfillment of their goal (Wilson, 2000).

Stoichiometry Problems

Stoichiometry problems are a fundamental type of chemistry problem in which the amounts of reactants and products for a chemical reaction are compared using ratios obtained from a balanced chemical equation. The problems are grounded in the concepts
of the mole, ratio, and proportion. Students encounter these stoichiometric relationships across many units in the Ontario Grades 11 and 12 chemistry courses including: mass balance, solution concentration, gas laws, energetics, rates of reaction, equilibrium, and electrochemistry.

**Design Lab**

A design lab is an ill-defined, lab based, problem solving task. The students are required to: (a) generate the research question, (b) select variables and identify controls, (c) design a procedure, (d) perform and revise the procedure as required, (e) analyze the data using their own method, and (f) interpret and communicate their findings. This definition of a design lab draws from the description of an open-inquiry lab (Bruck, Bretz, & Town, 2009), and from the internal assessment criteria specified by the International Baccalaureate Organization (International Baccalaureate Organization, 2007).

**Metacognition**

Schraw and Denison (1994) defined metacognition as the knowledge and regulation of one’s cognition. Schraw, Crippen, and Hartley (2006) elaborated upon this definition. Knowledge of cognition includes the awareness of what one knows, how one learns, what strategies one knows, and when one implements strategies. Regulation of cognition includes planning, monitoring, and evaluation. Planning involves one’s connection to previous knowledge, plan for using strategies, and use of time. Monitoring
is one’s self-checking at each stage of the task. Evaluation includes the learner’s appraisal of the outcome and reflection on what new knowledge he or she gained.

**Metacognitive Skills**

Metacognitive skills are the regulatory activities associated with solving problems (Brown, 1978). They involve the planning, monitoring, and evaluation components of metacognition.

**Metacognitive Framework**

The Metacognitive Framework is a pedagogical device I developed to guide the teacher’s instruction of problem solving and students’ approaches to problem solving (see Figure 1). It is a diagrammatic representation showing the metacognitive skills specific to solving complex chemistry problems and their association with the metacognitive categories of planning, monitoring, and evaluation. The theoretical foundation for this framework comes from the literature on models for problem solving (Polya, 1957; Resnick & Glaser, 1976) and metacognition (e.g., Schraw, Crippen, & Hartley, 2006).
When students enter the current work environment, they will face continuously changing demands that require them to be flexible and creative in the way they apply their knowledge. The Conference Board of Canada (2000) produced *Employability Skills 2000+* (2000) which outlines the skills students will need to cope with, advance in, and contribute towards today’s workplace. Desirable attributes for future workers include the abilities to “identify problems,” “be creative and innovative in exploring possible solutions,” and “be willing to continuously learn and grow” (Conference Board of Canada, p.2). Learners who are adept at problem solving will be better equipped to
function in this environment. In response to this, educators are called on to help students build their problem solving expertise.

Chemistry is a domain that affords students with opportunities to develop their thinking and problem solving skills. The mole concept is fundamental to many types of written and lab based problem solving tasks in chemistry. Previous research reveals high school students find mole problems challenging, and that their difficulties with these problems persist in university (Case & Fraser, 1999; Chandrasegaran, Treagust, Waldrip & Chandrasegaran, 2008; Cohen et al., 2000; Schmidt, 1990; Uce, 2009). The mole concept is a key element in stoichiometry problems. These problems can incorporate many aspects associated with a complex problem solving task. Specifically, such tasks require students to interpret and translate word problems into mathematical operations. They require students to integrate their understanding of multiple chemistry concepts within a variety of different areas of chemistry. They require students to find a way to link a number of steps together to fulfill the goal of the problem. Researchers can use stoichiometry problems as a means to explore students’ abilities to solve complex problems.

Students’ success at problem solving can be predicted by their use of metacognitive skills (Haidar & Naqabi, 2008; Howard, McGee, Shia & Hong, 2001; Rickey & Stacy, 2000; Rozencwajg, 2003). Swanson (1990) observed that metacognitive skill was a better predictor of students’ problem solving success than their aptitude; furthermore, higher levels of metacognitive skills compensated for low aptitude on
problem solving tasks. Kapa (2007) reported students’ use of metacognitive skills enabled them to transfer past knowledge to unfamiliar problems. This link between metacognition and problem solving has also been found in the science classroom. For example, Rickey and Stacy (2000) observed that successful problem solvers demonstrated better monitoring and regulation of thinking while solving chemistry problems. Haidar and Naqabi (2008) also found that deep conceptual learning was characteristic of students who demonstrated the metacognitive skills of knowing what the task requires, planning a strategy, monitoring their progress, and self-checking their work.

Students’ metacognitive skills can be improved through explicit instruction (Hartman, 2001a; Martinez, 1998; Schraw, 2001). Such instruction is most effective when teachers incorporate it into subject specific learning activities (Case & Gunstone, 2002; Gredler, 2009). The purposeful integration of metacognitive training into instruction improves students’ problem solving abilities (Haidar & Naqabi, 2008; Howard et al., 2001; Kapa, 2007; Rozencwajg, 2003; Schraw, Brooks, & Crippen, 2005, Swanson, 1990; Zakaria, Yazid, & Ahmad, 2009). Specifically, it provides learners with a transferable skill set for solving non-routine problems. Consequently, learners gain confidence that they can summon the skills required to solve unfamiliar problems; their self-efficacy is enhanced.

Educators can incorporate a variety of instructional strategies to promote the development of students’ metacognitive skills. Instructional methods that target the
planning, monitoring, and evaluation components of metacognition are particularly supportive to students’ problem solving (Hartman, 2001a; Kapa, 2007; Schraw, 2001). Collaborative problem solving activities help students to be more self-conscious about their thinking during both written and lab based problem solving tasks (Hartman, 2001a; Whimbey & Lochhead, 1986). Design labs offer further opportunities for students to practice their planning, monitoring, and evaluation skills (Davidowitz & Rollnick, 2003; Kipnis & Hofstein, 2008; Rickey & Stacy, 2000; White & Frederiksen, 2005).

My research has been designed to gain insight into students’ use of metacognitive skills in relation to their problem solving processes. By using a variety of data sources that include a metacognitive skills questionnaire, written and lab based complex problem solving tasks, and think aloud protocols, I endeavored to capture a rich picture of students’ thinking while problem solving. This research has potential to enrich our understanding of how students use metacognitive skills during problem solving activities. Furthermore, this study links instructional strategies to students’ acquisition of metacognitive skills and their problem solving abilities in high school chemistry. The outcomes of this study have valuable pedagogical implications; my findings may assist teachers to design instructional methods that support students to become more skilled at solving complex chemistry problems. In the broader sense, students may transfer these skills to other settings in which they are called upon to solve real world problems.
Overview of the Thesis

This thesis is organized into five chapters. The first chapter outlines my inspiration for undertaking this research, the purpose, the definition of terms, and the rationale. In Chapter 2, I present the theoretical basis and empirical evidence that guided my research. In Chapter 3, I describe the design and outline the analyses I implemented in this study. In Chapter 4, I present and analyze the data I collected. Finally, in Chapter 5, I interpret the outcomes of my study, discuss the limitations of my results, and offer suggestions for further research.
CHAPTER 2
LITERATURE REVIEW

The intent of my research was to investigate four research questions aimed at revealing: (a) the effect of purposeful metacognitive instruction on students’ use of metacognitive skills, (b) the effect of purposeful metacognitive instruction on students’ abilities to solve chemistry problems, (c) students’ use of metacognitive skills while problem solving, and (d) students’ use of the Metacognitive Framework as a model for problem solving. The purpose of this chapter is to present the literature that underpins my research project. This review of the literature endeavors to establish the theoretical basis for my study and provides an account of the empirical studies that led me to my investigation. The main fields of research that are relevant to my study are problem solving and metacognition. The review begins with an overview of problems and problem solving within the context of high school chemistry. I then describe different methods to assess problem solving. The subsequent sections focus on metacognition, methods for measuring metacognition, and the importance of metacognition to students’ learning processes. Finally, I present the research on metacognitive instruction that has formed the foundation for the intervention implemented in my study.

Problems and Problem Solving

Hayes (1989) defined a problem as a situation “whenever there is a gap between where you are now and where you want to be, and you don’t know how to find a way to
cross that gap” (p. xii). From their review of the literature, Resnick and Glaser (1976) described a problem as a new task for which specific instructions are not provided and which may be solved by applying previous knowledge. Problems may be further classified according to more specific characteristics. Cracolice, Deming, and Ehlert (2008) classified problems as algorithmic and conceptual. Students solve algorithmic problems by executing a routine set of procedures. In contrast, conceptual questions require students to map out their own unique solution to a question. Reid and Yang (2002b) made the case that algorithmic questions are not problems at all, but exercises. Such exercises allow the learner to practice and demonstrate what they already know. Bodner (1987) argued that the classification of a question as a problem or exercise depends on the interaction of the individual with the task. If the individual immediately has a method that leads to a solution to the question, then the question is an exercise. In contrast, if the individual is unaware of this method, the question becomes a problem for them.

Hollingworth and McLoughlin (2005, p. 69) described problems on a continuum from well-defined to ill-defined (see Table 1). On one end of the spectrum, well-defined problems have a prescribed method for finding the one correct solution. Such problems match the previous definitions for algorithmic problems (Cracolice et al., 2008) and exercises (Reid and Yang, 2002b). At the other extreme, ill-defined problems are novel problems that learners approach using a variety of methods to produce one of many possible solutions. In the literature, these are also referred to as open-ended problems. My
research uses selected written problems that are well-defined in some characteristics and ill-defined in others according to the descriptions provided by Hollingworth and McLoughlin (2005). These problems provide complete data and possess a correct answer. However, the concepts are not explicit and the solution process is unfamiliar to the students. I describe these as complex problems.

Table 1

*Comparing Well-Defined and Ill-Defined Problems*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Well-defined</th>
<th>Ill-defined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Complete</td>
<td>Incomplete or not given</td>
</tr>
<tr>
<td>Knowledge Domain</td>
<td>Well-defined</td>
<td>Ill-defined</td>
</tr>
<tr>
<td>Rules and Principles</td>
<td>Limited rules and principles in organized arrangement</td>
<td>Uncertainty about concepts and principles necessary for a solution</td>
</tr>
<tr>
<td>Solution Process</td>
<td>Familiar; knowable, comprehensible method</td>
<td>Unfamiliar; no explicit means for action</td>
</tr>
<tr>
<td>Answer</td>
<td>Clear goal, convergent; possess a correct answer</td>
<td>Uncertain, multiple or no solution; need to make judgments and evaluations</td>
</tr>
</tbody>
</table>

In the formal education setting, the evaluation of student achievement in math and science is often based on tasks with clearly defined goals and methods (Reid & Yang, 2002b). In contrast, real world problems are complex and often have ill-defined solution methods (Overton & Potter, 2008; Reid & Yang, 2002b). Students are more engaged in
problem solving tasks of this nature (Reid, 2000; Renkl, Mandl, & Gruber, 1996). Learners who are challenged by complex problems demonstrate higher motivation and persistence (Deci & Ryan, 2000). Csikszentmihalyi (1997) added that this challenge must be optimal, one that requires a learner’s skills to be fully involved in overcoming a challenge that is almost in balance with the capabilities of the learner. A growing concern of chemistry educators is that students are not acquiring adequate problem solving skills during chemistry courses (Bodner, 2003; Hollingworth & McLoughlin, 2005; Taasoobshirazi & Glynn; Teichert & Stacy, 2002). To address this need, chemistry teachers are called upon to incorporate more ill-formed problems into the problem solving tasks they present to students (National Research Council, 1996; American Association for the Advancement of Science, 1993). This way of teaching may provide students with more opportunities to develop the flexible expertise needed to tackle more complex problems.

Problem solving is the act of solving a problem. Martinez (1998) described problem solving as “the process of moving toward a goal when the path to that goal is uncertain” (p. 605). The process begins with a state of perplexity that provides the stimulus for learning something new. Attempts have been made to distill the complex process of problem solving into manageable steps that are broadly applicable. Polyá (1957) proposed a four-step model for solving mathematical problems. First, the learner must understand the problem. This involves identifying what is known and what relevant data are given, creating a representation of the problem that might include a diagram or
flow chart, and recognizing the various parts of the problem. Second, the learner devises a plan to find the connection between the given information and the goal of the problem. At this stage, the learner should recall other problems that may be similar to the new task or that may allow the learner to solve a part of the new problem. Third, the learner carries out the plan and checks each step. Lastly, the learner looks back at the solution to check for correctness, to propose alternate approaches, and to note how this solution might be useful to solve a different problem. However, Reid and Yang (2002b) commented that this model does not depict the way scientists approach open-ended problems. Polya’s model does not include the revision of strategies that is often a part of solving unfamiliar problems.

Resnick and Glaser (Resnick, 1976) presented a different model for problem solving. This model preserves aspects of Polya’s model while incorporating the back and forth feedback based revision process. The key features of this model are problem detection, feature scanning, and goal analysis. During problem detection, the learner searches their long term memory for a routine that will produce a solution to the task. If one is found, then the task is an exercise that can immediately be solved. If an applicable algorithm is not found, the task is identified as a problem and feature scanning is initiated. This phase involves a constant back and forth between the task and the learner’s long term memory. The learner re-examines the task in pursuit of some feature that connects the task to the learner’s previous knowledge. During goal analysis, the learner may isolate subtasks that can be solved using a familiar strategy. The problem is broken
down into a series of smaller problems for which the learner has routines to solve each subtask. Eventually, the problem solver must reassemble these subtasks to form an integrated solution to the original task. This method requires the learner to repeatedly check their progress and compare their solution at each stage to the original goal.

It is important for researchers and educators to understand what is involved during the problem solving process in order to be able to design instructional methods that support students’ problem solving. My study includes the implementation of instructional methods aimed at building students’ problem solving skills. I have incorporated aspects of the Polya and Resnick-Glaser models for problem solving into the Metacognitive Framework I designed to guide these instructional methods.

Problem Solving in Chemistry

Problem solving is an integral part of chemistry education. Chemistry problems may be qualitative in which students’ solutions require an explanation drawn from their conceptual knowledge base. Other problems are quantitative and require the learners to integrate their conceptual knowledge and numeracy skills. Such problems may be written or hands on investigative problem solving tasks. In chemistry, the mole is a rudimentary concept that forms the basis for many other types of chemistry problems such as stoichiometry problems. Past research reports that chemistry problems associated with the mole concept pose considerable challenge to chemistry students (BouJaoude & Barakat, 2003; Case & Fraser, 1999; Chandrasegaran et al., 2008; Cohen et al. 2000; Schmidt, 1990; Uce, 2009). Based on my own teaching experience, the mole concept
remains a challenging and intangible concept for many students. Consequently, I continue to explore alternative ways to present mole problems to the students. A review of the literature offers insight into why students struggle with problems that involve the mole. I highlight the following three areas of difficulties for students: (a) students’ access of knowledge from their long-term memory, (b) students’ difficulties applying math concepts to chemistry problems, and (c) students’ dependence on algorithms.

Reid and Yang (2000a, 2000b) emphasized the role of long-term memory during problem solving. Learners have a chemistry knowledge base stored in their long-term memory. They must find the link between the current problem scenario and the strategies they have stored in their long-term memory. Their past knowledge needs to assemble into a path forward that leads to a solution to the problem. These events are particularly challenging for students faced with open-ended problems because they are uncertain about what previous knowledge will be of use in the unfamiliar problem.

Chandrasegaran et al. (2008) outlined students’ difficulties connecting their math knowledge to chemistry problems. Many chemistry problems require students to translate word problems into mathematical statements. Stoichiometry problems combine the mole concept with ratio and proportion. Such problems require students to have a sound understanding of ratio and proportion that goes beyond their experience in purely mathematical settings.

Finally, the way students employ strategies may detract for their ability to solve complex mole problems. Two tools commonly employed by students during problem
solving are algorithms and heuristics. Algorithms are straightforward procedures that students select and apply to produce an answer. For example, in chemistry, moles are calculated by dividing mass by the molar mass. Frank, Baker, and Herron (1987) presented algorithms as an essential part but not the sole means of the problem solving process in chemistry. An aspect of problem solving requires the learner to select, modify, and apply the appropriate algorithms. Heuristics are general procedures that may or may not lead a student to a solution to the problem. For example, unit analysis may be used to solve multi-step stoichiometry problems. High school and university chemistry students typically seek algorithms to solve problems (Anamuah-Mensah, 1996; BouJaoude & Barakat, 2003; Bunce, Gabel, & Samuel, 1991; Case & Fraser, 1999; Chandrasegaran, et al., 2008; Gabel, Sherwood, Enoch, 1984; Herron & Greenbowe, 1986; Lythcott, 1990).

The research indicates that students’ dependence on algorithms impedes their problem solving process in a number of ways. Students who rely heavily on using algorithms lack deep conceptual understanding (Case & Fraser, 1999; Niaz & Robinson, 1992). This approach has been shown to limit students’ abilities to adapt and apply their previous knowledge to unfamiliar problems (Kapa, 2007). Lastly, it is associated with students’ struggles to link sequential steps together to solve complex problems (Lazonby, Morris, & Waddington, 1982). Frazer and Sleet (1984) provided empirical evidence of this in their study of students’ abilities to solve multi-step chemistry problems. In their study, students were asked to solve a complex, quantitative problem. After this attempt, the students were asked to solve a series of sub-problems inherent in the solution to the
main problem. The researchers determined some students could successfully solve each sub-problem but could not manage to solve the complete problem. They attributed this to an inability of the students to plan a solution to the problem. I have observed that when students initiate their problem solving process by summoning algorithms, they neglect to formulate a plan that links the algorithms together. The algorithm becomes a crutch for students.

Complex stoichiometry problems integrate the concepts of balanced chemical equations and the mole. These types of problems provide the ideal tool to investigate students’ problem solving processes. For this reason, I selected stoichiometry type problems for all problem solving tasks in my study.

**Inquiry Activities**

The laboratory component of chemistry courses provides a setting in which students can build their problem solving capacities. Brooks (2002) recommended that science teachers move away from cookbook style investigations and incorporate more student designed lab experiences. Shulman and Tamir (1973, p. 1112) described a classification of system for laboratory activities that reflects the degree to which students are given guidance from their instructor (see Table 2). The lab activity is divided into three components: the problem, ways and means, and answers. The problem refers to the purpose for the experiment. The ways and means refer to the materials, equipment, and procedure for the experiment. Answers refer to the outcomes of the experiment. The amount of information provided to the student is described as given or open.
Table 2

*Levels of Openness in the Teaching of Inquiry*

<table>
<thead>
<tr>
<th>Level</th>
<th>Problem</th>
<th>Ways &amp; Means</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Given</td>
<td>Given</td>
<td>Given</td>
</tr>
<tr>
<td>1</td>
<td>Given</td>
<td>Given</td>
<td>Open</td>
</tr>
<tr>
<td>2</td>
<td>Given</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>3</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
</tbody>
</table>

Bruck, Bretz, and Town (2009) further elaborated upon this classification system to include clearer descriptions of the type of inquiry activity and the parts of the activity (see Table 3). In the table, P indicates that the instructor provides the information to the student, and NP indicates the instructor does not provide information to the student. Using this system, a design lab falls into the category of an open inquiry.

Table 3

*Classification of Inquiry Activities*

<table>
<thead>
<tr>
<th></th>
<th>Level 0 Confirmation</th>
<th>Level ½ Structured Inquiry</th>
<th>Level 1 Guided Inquiry</th>
<th>Level 2 Open Inquiry</th>
<th>Level 3 Authentic Inquiry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem or question</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>NP</td>
</tr>
<tr>
<td>Theory or background</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>NP</td>
</tr>
<tr>
<td>Procedures or design</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>NP</td>
<td>NP</td>
</tr>
<tr>
<td>Method of analysis</td>
<td>P</td>
<td>P</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
</tr>
<tr>
<td>Communication of results</td>
<td>P</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
</tr>
<tr>
<td>Conclusions</td>
<td>P</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
</tr>
</tbody>
</table>
Collaboration in Problem Solving

Recent changes in the Ontario Science Curriculum reflect the need for teachers to expose students to the way scientists work in the real world. The new curriculum includes an umbrella unit on Scientific Investigation Skills that educators are expected to integrate across all content areas (Ontario Ministry of Education, 2008). Authentic scientific inquiry involves scientists working in teams, and this collaboration is essential for advancement in science. Extensive research has shown that students benefit from collaborative activities as well. Johnson and Johnson (1991) reported that students who participate in carefully structured group work demonstrate higher engagement with the task and think at a higher level. Such cooperative learning environments have also been shown to enhance students’ problem solving skills in chemistry (Bilgin, 2005; Cooper, Cox, Nammouz, Case & Stevens, 2008; Mahalingam, Schaefer, & Morlino, 2008; Reid & Yang, 2002a; Wood, 2006). Collaboration during problem solving is particularly effective for students when they are working on open-ended problems. Reid and Yang (2002a, 2002b) suggested reasons for this. The students combine their background knowledge, share expertise, and generate a greater range in strategies. Overall, the students expand their problem solving capacities by combining their individual expertise. Hartman (2001a) added that students find errors and become more aware of their misconceptions when they work with a partner.
**Think Aloud Pair Problem Solving**

Whimbey and Lochhead (1986) developed the Think Aloud Pair Problem Solving (TAPPS) method of conducting collaborative problem solving sessions in the classroom. The method was developed in part to encourage students to be more actively involved in problem solving. TAPPS involves students working in pairs. Each member of the pair is assigned a specific role as either the listener or the problem solver. The problem solvers are instructed to verbalize all of their thoughts while working through the problem. The role of listeners is to encourage the problem solvers to articulate their thinking throughout the problem solving process. This includes: (a) encouraging the problem solver to keep verbalizing throughout the session, (b) working through each step described by the problem solver as a way to check the accuracy and logic of the problem solver, and (c) pointing out flaws to the problem solver but not making corrections to the solution. The TAPPS technique engages both members of the pair in the thinking associated with solving the problem. Thinking aloud “helps students to think more precisely, carefully, and systematically” (Hartman, 2001a, p. 61).

Empirical evidence of the effectiveness of the TAPPS method in chemistry problem solving has been collected. Bilgin (2006) investigated the effects of the TAPPS method on undergraduate students’ abilities to solve both algorithmic and conceptual chemistry students. The participants were divided into two groups. A logic test was used as a covariate to correct for initial differences between the groups. Both groups were instructed in the use of Polya’s problem solving method. Only the experimental group
participated in TAPPS activities during the study. The experimental group out performed the control group on both the algorithmic and conceptual tests. A weakness of this study is the use of only multiple choice questions as a measure of students’ problem solving abilities. Multiple choice questions allow students to guess an answer and do not require the students to demonstrate their method for obtaining a solution.

Jeon, Huffmann, and Noh (2005) studied the effects of a TAPPS method and the Polya method of problem solving on the abilities of Grade 11 chemistry students to solve gas law problems. The study involved three groups of students: one experimental group was instructed in the use of the Polya method, the second experimental group experienced both the Polya method and the TAPPS method, and the third was not exposed to either method. Both experimental groups scored higher on the test than the control group. Further analysis of the students’ solutions to the problems revealed that the TAPPS group demonstrated a better conceptual understanding of the problems.

My research incorporated the TAPPS method for the think aloud problem solving sessions as a method of data collection and as a teaching method to encourage students to think more carefully and methodically about their problem solving processes.

Assessment of Problem Solving

Researchers and practitioners have proposed various methods to assess problem solving. A mark scheme is plausible for algorithmic problems where a predictable solution exists. Such a mark scheme awards points for the students’ selection and execution of the appropriate algorithms. However, problems with less clearly defined
solutions demand a different assessment approach. Zakaria, Yazid, and Ahmad (2009) developed a mark scheme that gives the marker more flexibility to evaluate students’ different approaches to solving a problem. The method is based on Polya’s (1957) problem solving model. A solution is evaluated on understanding the problem, planning a strategy, performing the strategy and the correctness of the solution. This scheme focuses on the problem solving process in addition to the correctness of the solution. A disadvantage of this method is the difficulty the marker may have in identifying the elements of the process in a student’s solution.

Rubrics are another method for assessing problem solving tasks. Rubrics are scoring guides that include a list of performance criteria and a description of the different levels to which the performance criteria may be fulfilled. Mertler (2001) identified two types of rubrics: holistic and analytic. Holistic rubrics score an overall process or product whereas analytic rubrics score the individual components of a product or process. The selection of the type of rubric depends on the purpose of the assessment. In comparison to holistic rubrics, analytic rubrics provide more feedback to the student. Mertler (2001) argued that analytic rubrics are better suited for formative assessments and holistic rubrics for summative assessments. Furthermore, Nitko (2001) suggested the use of holistic rubrics to assess students’ solutions to open-ended tasks where more than one reasonable approach exists. For complex problem solving tasks, a holistic rubric may be the more appropriate choice.
The research describes a variety of holistic rubrics that can be used to evaluate students’ solutions to problems. Piaget’s classification of learners’ understanding into “no understanding,” “partial understanding,” and “sound understanding” guided earlier assessment methods for problem solving in mathematics (Copeland, 1984). This model was further developed by Haidar (1997) to include five descriptors: “no understanding” (NU), “specific misconception” (SM), “partial understanding with specific misconception” (PU/SM), “partial understanding” (PU), and “sound understanding” (SU). Haidar and Naqabi (2008) quantified this model by assigning points to each category: NU = 1, SM = 2, PU/SM = 3, PU = 4, and SU = 5. This type of rubric presents the following challenges to the marker. The marker must have a clear understanding of the descriptors in order for the assessment to be both reliable and valid. The marker may find it difficult to identify a specific misconception. Lastly, the distinction between PU/SM and PU is ambiguous.

The need for rubrics that employ clear language is essential to both students and teachers. Students should be able to interpret their level of performance relative to the teacher’s expectations. Teachers need to have a clear sense of the performance levels in order to provide valid and reliable assessments of students’ work. Researchers and practitioners have attempted to address these concerns. As an example, Mertler (2001, para. 3) provided a template for holistic rubrics (see Table 4). An advantage of this rubric is that the descriptors are easier to interpret. A limitation of this rubric is that a 5-point scale does not produce a finely calibrated set of scores.
Table 4

*Template for Holistic Rubrics*

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Demonstrates complete understanding of the problem. All requirements of task are included in the response.</td>
</tr>
<tr>
<td>4</td>
<td>Demonstrates considerable understanding of the problem. All requirements of task are included</td>
</tr>
<tr>
<td>3</td>
<td>Demonstrates partial understanding of the problem. Most requirements of task are included in the response.</td>
</tr>
<tr>
<td>2</td>
<td>Demonstrates little understanding of the problem. Many requirements of task are missing.</td>
</tr>
<tr>
<td>1</td>
<td>Demonstrates no understanding of the problem.</td>
</tr>
<tr>
<td>0</td>
<td>No response/task not attempted.</td>
</tr>
</tbody>
</table>

A solution to this limitation may be an analytic rubric that assigns a level to each criteria that can then be summed to provide a total point score. Jeon et al. (2005) proposed such a scoring system for problem solving. This method better differentiates between the calibers of students’ solutions to problems. The marker scores the solution out of three points on each of five criteria: identifying the given variables, demonstrating conceptual knowledge, recalling the related law, progressing in an organized manner, and executing a mathematical solution. A specific descriptor is provided for the number of points awarded for each criterion. The authors selected criteria to match the qualities of competent problem solvers. The holistic rubric for problem solving that I devised for use in my research combined the general descriptors suggested by Mertler (2001) with the more detailed criteria suggested by Jeon et al. (2005). I was also attentive to suggestions
made by Tierney and Simon (2004) to assess the same performance criteria across each level and use consistent language for these criteria.

**Metacognition**

Flavell (1976) pioneered research in metacognition. He defined metacognition as “one’s knowledge concerning one’s own cognitive processes and products” and “the active monitoring and consequent regulation and orchestration of these processes” (p.232) to achieve a goal or objective. Lajoie (2008) worded this simply as “thinking about one’s own thinking” (p. 470). Over time, researchers have elaborated upon this definition. Flavell (1979) described a model for cognitive monitoring that divided metacognition into metacognitive knowledge and metacognitive experiences. He further described how each interacts with goals, tasks, and strategies. In this model, knowledge refers to: (a) knowledge of oneself or others as learners, (b) knowledge of what a task requires, and (c) knowledge of strategies that can be used to achieve goals. A metacognitive experience involves the control and regulation of one’s cognitive processes. Metacognitive experiences “occur in situations that stimulate a lot of careful, highly conscious thinking” (p. 908). When learners assess their progress during a task, a metacognitive experience is activated. These experiences may lead the learners to revise their goals and use of strategies.

Baker and Brown (1984) separated metacognition into knowledge about cognition and the self-regulation of cognition through planning, monitoring effectiveness, revising, and evaluating the outcome. As the definition of metacognition evolved to include self-
regulatory processes, the overlap between metacognition and self-regulated learning (SRL) became evident. Pintrich (2000) defined SRL as “an active, constructive process whereby learners set goals for their learning and then attempt to monitor, regulate, and control their cognition, motivation, and behavior, guided and constrained by their goals and the contextual features in the environment” (p. 453). In their review of the literature, Dinsmore, Alexander, and Loughlin (2008) foresaw a need to more clearly delineate the two terms. They proposed that metacognition and SRL share the common element of self-regulation. The constructs are distinct in that SRL includes the interaction between the learner and the environment whereas metacognition focuses on the self-reflective cognitive process of the learner.

Schraw et al. (2006) located metacognition as a part of self-regulated learning (SRL). They identified metacognition as the skills that make it possible for learners to understand and regulate their learning. Their model divided metacognition into knowledge of cognition and regulation of cognition. Knowledge of cognition is subdivided into declarative, procedural, and conditional knowledge. Declarative knowledge is the knowledge of one’s learning process including an awareness of when one understands or not and how one learns (Gourgey, 2001). Procedural knowledge is one’s knowledge about strategies. Conditional knowledge is one’s understanding of when strategies are appropriate. Regulation of cognition is subdivided into planning, monitoring and evaluation. Planning requires the learner to draw on relevant previous knowledge, identify goals, map out the use of strategies, and manage resources such as
time and effort. Monitoring is the recursive process of self-checking and revising of strategies that occurs during a learning task. Evaluation is the appraisal of the final outcome and consolidation of new knowledge acquired. I have adopted this model of metacognition for my study because it aligns well with the problem solving process. It shares many common elements with the models for problem solving described by Polya (1957) and Resnick and Glaser (1976). These elements are: (a) making a connection to previous knowledge, (b) planning of the solution, (c) monitoring each stage of the solution, and (d) evaluating the final answer. The Metacognitive Framework I developed links these elements of problem solving to this model for metacognition.

Each phase of the problem solving process involves metacognitive functions. In an interview with Shaughnessy (2008), Flavell noted that the puzzlement or “cognitive disequilibrium” (p. 226) experienced by learners when they are faced with a problem triggers metacognitive activities. Flavell (1976) identified metacognitive behaviors that are applicable to problem solving. The learners should be persistent in their attempts to solve problems even when discouraged because of faulty attempts. The learner should make a conscious effort to learn from all problem solving experiences, and learn how to summon this knowledge in new problem solving scenarios. The learners should compare the outcomes of their problem solving to the original goal of the task.

**Measuring Metacognition**

Measuring metacognition has been an ongoing challenge to researchers. Self-report questionnaires have been developed to provide a quantitative measure of an
individual’s metacognition. Schraw and Dennison (1994) developed the Metacognitive Awareness Inventory. The questionnaire measures the two main aspects of metacognition, knowledge of cognition and regulation of cognition in adults. This questionnaire formed the basis for the Inventory of Self-Regulation developed by Howard, McGee, Shia, and Hong (2000) for use with 12-18 year olds to be used in the context of problem solving. Haidar and Naqabi (2008) subsequently selected this inventory to measure metacognition in Grade 11 chemistry students. Exploratory factor analysis of this inventory by the researchers produced five factors that were named: awareness of cognition, planning, monitoring and self-checking, self-appraisal and engagement in task. Further statistical analysis indicated a significant correlation amongst four of the five factors and the students’ performances on stoichiometry problems. The researchers found no significant correlation between students’ awareness of cognition and their abilities to solve stoichiometry problems. Hence problem solving in chemistry may depend more on the regulation of cognition than on the awareness of cognition.

Cooper and Sandi-Urena (2008) developed the Metacognitive Activities Inventory (MCAI) that focuses on the regulation of cognition (i.e., planning, monitoring, and evaluation). The MCAI specifically addresses students’ metacognitive skillfulness during problem solving in chemistry. Responses from 817 university chemistry students confirmed the validity and reliability of the instrument (Cooper & Sandi-Urena, 2008).

Questionnaires offer researchers the advantage of being able to assess the metacognition of a large number of participants in a short period of time, and the analysis
of the data is straightforward. At the same time, questionnaires have limitations. Students’ responses to questionnaires may be inaccurate because the responses are gathered retrospectively (Helms-Lorenz & Jacobse, 2008). Another limitation is that students completing self-report questionnaires may report what they think they should do and not necessarily what they do (Schunk, 2008; Thorndike, 2005).

To address these limitations, other methods to examine students’ metacognition have been developed. For example, think aloud protocols have been used to provide qualitative evidence of students’ use of metacognition during problem solving (Pintrich, Wolters, & Baxter, 2000). During the think aloud protocol, students articulate their thoughts while they perform a problem solving task. This method allows observers to explore the nuances of students’ problem solving processes. The concurrent verbalization method is reported to create a snapshot of the learners’ natural problem solving behaviors (Stillman & Galbraith, 1998). A further benefit of the think aloud protocol is that the researcher may be able to distinguish between shallow and deep metacognitive processes (Veenman, 2008). A challenge to researchers using think aloud protocols is the difficulty they may experience in interpreting the verbal evidence of students’ metacognition.

Data from questionnaires and think aloud protocols complement each other. Using both may produce more detailed data about learners’ metacognitive skills while problem solving. For this reason, a multi-method approach to measuring metacognitive skills is recommended (Cooper et al., 2008; Ericsson & Simon, 1980; Garner &
Alexander, 1989; Georghiades, 2004). My research used both the MCAI and think aloud protocols to examine students’ metacognitive skillfulness.

The Outcomes of Metacognition

Positive learning outcomes are associated with students’ use of metacognitive strategies. Two such outcomes relevant to my study are students’ improved conceptual understanding and problem solving abilities. Metacognitive activities bring about conceptual change (Georghiades, 2000; Hennessey, 1999; Yuruk, Beeth, & Andersen, 2009). Conceptual change learning (CCL) is the revision of a learners’ previous understanding of a concept by adding new knowledge to it (Tastan, Yalçinkaya, & Boz, 2008). CCL is rooted in the constructivist approach to learning. Learning is initiated when students identify a flaw in their understanding and seek to build on their knowledge (Brooks, 2002). The process of learning is a continuum that begins with a learner’s misconception and gradually progresses to a more accurate conceptual understanding. Conceptual change learning (CCL) models are prominently featured in science education research (Case & Fraser, 1999; Georghiades, 2000; Hennessey, 1999; Yuruk et al., 2009). In chemistry education, conceptual change texts have been used to improve students’ understanding of the mole and stoichiometry (Tastan, Yalçinkaya, & Boz, 2008; Uce, 2009). This instructional method employs texts that guide students to make connections between prior knowledge and a new task. A sequence of metacognitive steps is inherent in CCL (Georghiades, 2000). The learner must know their current understanding, assess the need to refine this understanding, and select strategies to bring about the change.
Students’ metacognitive skill development is important to their abilities to solve math and science problems (Haidar & Naqabi, 2008; Howard et al., 2001; Kapa, 2007; Rozencwajg, 2003; Schraw, Brooks & Crippen, 2005, Swanson, 1990; Zakaria, Yazid, & Ahmad, 2009). Haidar and Naqabi (2008) studied students’ understanding of stoichiometry in Grade 11 chemistry, their use of metacognitive strategies and the relationship between both. Their results revealed that students’ understandings of stoichiometry could be predicted by their use of metacognitive strategies. Based on their findings, Haidar and Naqabi (2008) recommend that chemistry educators teach their students to use metacognitive strategies. Three aspects of their research open avenues for future research. First, the stoichiometry problems used to test students’ understanding of the concept were highly algorithmic. Exploring students’ approaches to more complex problems would extend the research. Secondly, a more direct link between metacognitive skills and problem solving skills could be investigated if the survey of students’ metacognition occurred concurrently with the problem solving tasks. Lastly, students’ use of metacognitive skills could be explored in more depth using a variety of methods that could include recorded think aloud protocols.

**Metacognitive Instruction**

Metacognition is teachable (Schraw, 2001). Explicit instruction is needed to help students improve their metacognitive awareness (Hartman, 2001a; Martinez, 1998). Instruction that encourages students to reflect on how they think, learn, remember, and perform tasks may help students to develop control over their own learning. Hartman
(2001b) called this “teaching for metacognition” (p. 149). This instruction is more effective when the instructors present metacognitive strategies within the context of a subject area, teach these strategies explicitly, provide opportunities for the students to practice them, and integrate them into regular learning activities (Case & Gunstone, 2002; Gredler, 2009).

My intervention research made use of several instructional strategies intended to support students’ metacognitive skill development. These included collaborative problem solving activities, design labs, and regulatory checklists adapted from the Metacognitive Framework I developed for this study. The positive effects of collaboration on students’ abilities to problem solve were described earlier. This improvement is partially attributable to an increase in students’ metacognitive awareness as a result of the verbal exchanges that occur between students while solving problems in small groups (Kuhn & Dean, 2004; Schraw & Moshman, 1995). Think aloud protocols are also an effective instructional strategy to improve students’ metacognitive awareness (Hartman, 2001a; Kramarski & Mevarech, 2003). Lonning (1993) reported that students gain clarity in their thinking by discussing their ideas with others. When learners are called on to externalize their thought processes, the learners become more cognizant of their own thinking (Jeon et al., 2005).

Design labs employ the use of metacognitive skills (Davidowitz & Rollnick, 2003; Kung & Linder, 2007; Rickey & Stacy, 2000; White & Frederiksen, 2005). Kipnis and Hofstein (2008) investigated how Grades 11 and 12 students used metacognition
during chemistry design labs. Analyses of the data from observing students during the lab activities, student interviews, and student reflections revealed that specific aspects of metacognition came into play at various points. Arriving at the purpose of the experiment demonstrated learners’ metacognitive declarative and procedural knowledge.

Experimental design and modification demonstrated the planning part of the regulation of cognition. While drawing conclusions, the students used conditional knowledge. Monitoring and evaluating were evident through all parts of the activity. The researchers’ method for coding the students’ transcripts used the metacognitive categories of knowledge of cognition, planning, monitoring, and evaluation. This coding method also guided me in my analyses of the TAPPS protocols and student lab reports.

Previous research explored students’ use of metacognitive skills during design labs. However, the potential for these activities to provide students with an opportunity to develop their metacognitive skills has not been investigated. Inquiry activities stimulate active reflection in the students that leads to a better conceptual understanding of the problem under investigation (Schraw et al., 2006). During inquiry activities, two inquiries occur simultaneously: the domain specific inquiry and students’ inquiry into their own learning. White and Frederiksen (2005) called this “inquiry about inquiry” (p. 215). As both inquiries proceed, students become increasingly self-aware and self-improving. I have included design labs as a metacognitive skill-building tool. Such skills may be transferable and enhance a student’s problem solving capabilities outside the lab setting.
Regulatory checklists are one tool that can be adapted to both written and lab-based problem solving tasks. Regulatory checklists may be worded as self-questions at the planning, monitoring, and evaluating phases of the task. Planning questions include: “What is my goal? … What kind of information and strategies do I need?” (Schraw, 2001, p. 11). Monitoring questions include: “Am I reaching my goals? … Do I need to make changes?” (Schraw, 2001, p. 11). Evaluation questions include: “Have I reached my goal? … Would I do things differently next time?” (Schraw, 2001, p. 11).

The use of self-questions was further investigated by Baird (1986). The goal of his study was to help high school science students become more thoughtful learners. He provided students with a checklist of questions to consider during problem solving activities. Key questions he included were: “What do I know about the topic? … Have I read the information fully and carefully? … How do the parts relate to each other? … What will I need to do in order to complete the task? … How will I approach the task? … How does this new knowledge compare with what I used to think?” (p. 270). Hartman (2001a) recommends that teachers provide self-questions to guide students through lab based problems. An example of a planning question is, “What are all the critical variables that need to be considered?” (p. 58). A monitoring question is, “Does the research design validly test the hypothesis?” (p. 58). An evaluation question is, “How effective was my experimental design” (p.58). I have incorporated key aspects of planning, monitoring, and evaluation from the work by Schraw (2001), Baird (1986), and Hartman (2001a) into the Metacognitive Framework I designed to guide my study.
**Intervention Studies**

Previous intervention studies provide evidence of the importance of metacognitive instruction in supporting students’ learning. Specifically, metacognitive instruction promotes improved retention of knowledge, transfer of knowledge to unfamiliar settings, and conceptual learning. The Cognitive Acceleration through Science Education program was a UK based intervention study aimed at improving the thinking skills of students aged 11-14 years (Adey & Shayer, 1994). Metacognition was fundamental to this study. The students participated in 16 lessons each year over a two-year period. Each lesson included a problem that was resolved through group work in which the students were explicitly directed to reflect upon their problem solving process. Results of the study indicated that students who participated in the program demonstrated improved achievement that persisted for years following the study. Another noteworthy outcome of the project was that this improvement extended beyond the science domain. Georghiades (2000) extended this research by investigating younger students. He observed that Grade 5 learners who received metacognitive instruction demonstrated deeper conceptual learning than the control group. These learners were able to transfer their knowledge to new settings and also retained their understanding over a longer duration.

The Project to Enhance Effective Learning (PEEL) was an extensive longitudinal study of secondary school students across many subject areas (Baird & Mitchell, 1987). The overarching aim of this study was to help students become more thoughtful learners.
Numerous instructional methods were developed and continuously revised based on feedback from the participating teachers and students. Questionnaires, discussions, and journal about learning and metacognitive self-question checklists were among the teaching strategies used to raise students’ awareness of their thinking and learning.

Fifteen qualitative data collection methods that included interviews, classroom observations, analysis of student work, audio and video recordings were used. The study showed that the students’ control over their learning increased and that their conceptual understanding improved. This project produced a rich body of anecdotal evidence of the gains made by students; however, changes in the students’ academic achievement were not measured.

Kapa (2007) designed a computerized learning environment for math students aged 13-14 years. The purpose of the study was to determine the effect of providing metacognitive support to the learners at various stages of the problem solving process on their abilities to solve structured (near transfer) and open-ended (far transfer) problems. Kapa divided the problem solving process into six steps that were closely related to Polya’s (1957) problem solving model with the addition of a last step that involved the learner’s use of feedback to make corrections. Kapa identified key metacognitive functions involved in each step thereby revealing how Polya’s model incorporated metacognitive skills. Two examples will follow. A metacognitive function associated with problem identification requires the learner to distinguish between relevant and irrelevant information in the problem. A metacognitive function associated with planning
requires the learner to select appropriate heuristics. The intervention consisted of computerized metacognitive questions activated at different points while the students worked through problems. These questions were similar to those in both the Schraw (2001) and Baird (1986) regulatory checklists. The study also included audio-recorded pre- and post-intervention think aloud sessions. Kapa’s analyses of these data revealed two outcomes. First, learners who experienced the metacognitive support questions during all stages of problem solving showed the biggest increase in their use of metacognitive skills. Second, learners’ exposure to the metacognitive questions at any stage of problem solving improved their ability to solve open-ended problems. Overall, the ability of a learner to transfer prior learning to unfamiliar contexts is linked to a learner’s metacognitive skill. This study has influenced my research methodology in two ways. I incorporated many of the metacognitive functions identified by Kapa into the Metacognitive Framework I designed for this study. I also incorporated verbal protocols to elucidate students’ thinking while problem solving.

Hennessey (1999) conducted Project META (Metacognitive Enhancing Teaching Activities). The study explored how metacognitive instructional strategies affected students’ conceptual understanding in science. Extensive data were collected over three years for science students in Grades 1 through 6. Throughout this period, the teachers implemented instructional strategies that encouraged students to share and debate their conceptions with each other. Hennessey identified students’ metacognitive behaviors during the verbal protocols. For example, evidence of students’ reasoning was
demonstrated by their explanations of their conceptions and awareness of the limitations of their understanding. One outcome of Hennessey’s analyses was that students exhibited different levels of metacognitive thought. My analyses of the TAPPs protocols in my study were influenced by this because I was made aware of the potential to observe different degrees of sophistication in students’ use of metacognitive skills.

An intervention study by Yuruk et al. (2008) investigated the effect of teaching activities designed to promote students’ use of metacognition in high school physics. The instructional methods incorporated journal writing, debate, discussions, and concept mapping as a means to improve students’ metacognition. The researchers collected samples of the students’ work and coded it for qualitative evidence of the students’ use of metacognition. Yuruk et al. (2008) reported that students in the experimental group developed a better and more persistent conceptual understanding of force and motion. The study implemented a pre- and post-test of students’ abilities to solve to conceptual physics problems. Similar studies investigating the impact of metacognitive instructional strategies on learning in high school chemistry have not yet been reported. Hence I used a pre-and post-test measure of students’ problem solving abilities in chemistry.

My review of the intervention studies that employed metacognitive instruction reveals pathways for research that have not yet been addressed. Past research has focused on students under the age of 14 (Adey & Shayer, 1994; Georghiades, 2000; Hennessey, 1999; Kapa, 2007). Previous studies have been specific to the subject areas of math (Kapa, 2007) and physics (Yuruk et al., 2008). Hence, senior high school chemistry
students have not been studied. Furthermore, students’ abilities to solve problems that combine abstract conceptual and computational components have not been investigated.

**Chapter Summary and Next Steps**

My review of the literature suggests that students’ use of metacognitive skills enables their problem solving (Haidar & Naqabi, 2008; Howard et al., 2001; Kapa, 2007; Rickey & Stacy, 2000; Rozencwajg, 2003; Swanson, 1990). Students’ development of metacognitive skills is promoted through explicit instruction (Case & Gunstone, 2002; Gredler, 2009; Hartman, 2001a; Martinez, 1998; Schraw, 2001). A review of the methods used to determine students’ metacognitive skills provides a rationale for a combined approach that uses a questionnaire and verbal protocols (Cooper et al., 2008; Ericsson & Simon, 1980; Garner & Alexander, 1989; Georghiades, 2004). Schunk (2008) proposes new directions for research studies on metacognition. He identifies a need for studies that link changes in a learner’s metacognitive process to both instructional methods and changes in a learner’s academic performance. My research study addresses this call and investigates areas that to date are not represented in the literature. Previous research has not explored the impact of metacognitive instruction on high school students’ abilities to solve complex chemistry problems. Previous studies have not investigated the use of design labs as an instructional strategy to build students’ metacognitive skills. Studying the effect of purposeful metacognitive instruction on students’ use of metacognitive skills and their abilities to solve complex stoichiometry problems within the context of high school chemistry will contribute to the existing research.
CHAPTER 3

METHODOLOGY

The purpose of my study was to explore students’ use of metacognitive skills during problem solving activities and to determine how explicit metacognitive instruction affects their use of metacognitive skills and their problem solving abilities. My research was designed as a quasi-experimental intervention study. The intervention involved instructional strategies aimed at building students’ metacognitive skills. A Metacognitive Framework that contained metacognitive skills specific to problem solving in chemistry guided the intervention. I employed a variety of data collection methods. Quantitative data were obtained from pre- and post-test measures of problem solving abilities using problem solving tasks and metacognitive skillfulness using a self-report questionnaire. In the absence of a control group for this study, these data collection events were field tested with a pilot group during the semester prior to the actual study. Data on students’ metacognitive and problem solving processes were also collected for the study group from the following sources: (a) think aloud pair problem solving (TAPPS) protocols, (b) an exit interview with the classroom teacher, (c) the students’ lab reports for two design labs, and (d) a survey of students’ use of the Metacognitive Framework. All instruments were designed and selected to integrate with normal classroom learning activities.
Setting and Participants

The setting for this study was a high school located in a medium sized city in Eastern Ontario. The student population is diverse in culture and socio-economic background. Students from both urban and rural neighborhoods attend the school. While I am a science teacher at the school, I did not teach any of the students in this current study prior, during, or after the study. The students who participated in my research were enrolled in the Ontario Grade 11 Chemistry University Preparation (SCH3U) course. The curriculum for the course is specified by the Ontario Ministry of Education (2008). Students receive their first exposure to chemistry specific problem solving through written word problems and in the laboratory setting in this course. During my informal discussions with experienced science teachers, they report that the Grade 11 course sorts students who can problem solve from those who have difficulty with problem solving.

The students for my research were selected through a convenience sample. During the first semester of the 2009 school year, I field tested the self-report questionnaire of metacognitive skillfulness and the problem solving tasks in a Grade 11 class taught by the same teacher as the subsequent study group. I will refer to the class from the first semester as the pilot group for my subsequent analyses. This provided some measure of the maturation that could be expected during the semester. The actual study occurred during the second semester of the 2009 school year. The teacher for the pilot and study groups was an experienced grade 11 chemistry teacher who enthusiastically volunteered to participate in my research. The pilot group had 26 students; however, not all students
completed the self-report questionnaire of metacognitive skillfulness and the problem solving tasks. This resulted in a sample size ranging from 18 to 26 students. The study group began with 22 students; however, one student withdrew from the course prior to the start of my study resulting in a sample size of 21 students.

**Intervention Design**

The intervention occurred over a 10-week period in which the teacher implemented a set of instructional strategies that provided students with the opportunity to develop key metacognitive skills associated with problem solving in chemistry. The intervention period spanned three units of study: Quantities in Chemical Reactions, Solutions and Solubility, and Gases and Atmospheric Chemistry.

**Developing the Metacognitive Framework**

I designed the Metacognitive Framework (see Figure 1) as an instructional tool to focus the teacher’s instructional strategies and the students’ problem solving efforts on the metacognitive skills relevant to problem solving. The framework is an amalgamation of the problem solving models developed by Polya (1957) and Resnick and Glaser (1976) with the model for metacognition described by Schraw, Crippen, and Hartley (2006). It identifies the problem solving behaviours associated with the knowledge of cognition, planning, monitoring, and evaluation components of metacognition. The Metacognitive Framework incorporates elements of the regulatory checklists presented by Baird (1986), Hartman (2001a), and Schraw (2001). The framework was made specific to problem solving in chemistry by including elements of two inventories designed for measuring
metacognitive skillfulness: the inventory of Metacognitive Self-Regulation (Howard et al., 2000), and the MCAI (Cooper & Sandi-Urena, 2009). The connection between each element of the Metacognitive Framework and the literature is shown in Table 5. I subsequently adapted the Metacognitive Framework into two metacognitive checklists for use by Grade 11 chemistry students: one for pen and paper problem solving tasks (see Appendix A) and one for design lab problems (see Appendix B). This was done to provide the students with a template for problem solving that would remind them about key metacognitive skills.

**Instructional Strategies**

Throughout the intervention, the students were exposed to the following instructional strategies aimed at developing students’ metacognitive skills. Early in the intervention, the teacher directed a group brainstorming activity in which students were called upon to think about and share their own approach to problem solving. One goal of this activity was to raise students’ awareness of their thinking while solving problems. During this exercise, the teacher guided the students towards building the Metacognitive Framework. Throughout the intervention, the teacher consistently modeled problem solving using the Metacognitive Framework. The teacher explicitly reminded the students of the framework each time a new type of problem was introduced. This was facilitated by presenting example problems on handouts with the metacognitive checklist on it (see Appendices A and B).
The two TAPPS protocols (Hartman, 2001a; Whimbey & Lochhead, 1986) acted as a metacognitive instructional strategy for all students in the study group and a source of data for a randomly selected sample from this group. As an instructional strategy, the

### Table 5

**Development of the Metacognitive Framework**

<table>
<thead>
<tr>
<th>Element from the Metacognitive Framework</th>
<th>Connection to the Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Knowledge</strong></td>
<td></td>
</tr>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td>Baird (1986), Cooper &amp; Sandi-Urena (2009), Hartman (2001a), Poly (1957), Resnick &amp; Glaser (1976)</td>
</tr>
<tr>
<td><strong>Plan</strong></td>
<td></td>
</tr>
<tr>
<td>Read the problem</td>
<td>Baird (1986), Cooper &amp; Sandi-Urena (2009), Howard et al. (2000)</td>
</tr>
<tr>
<td>Determine the goal</td>
<td>Cooper &amp; Sandi-Urena (2009), Hartman (2001a), Howard et al. (2000), Polya (1957), Schraw (2001)</td>
</tr>
<tr>
<td>Sort the given information</td>
<td>Cooper &amp; Sandi-Urena (2009), Howard et al. (2000), Poly (1957), Resnick &amp; Glaser (1976)</td>
</tr>
<tr>
<td>Breaking the problem down</td>
<td>Cooper &amp; Sandi-Urena (2009), Hartman (2001a), Howard et al. (2000), Polya (1957), Resnick &amp; Glaser (1976)</td>
</tr>
<tr>
<td>Relationships between quantities</td>
<td>Howard et al. (2000), Resnick &amp; Glaser (1976)</td>
</tr>
<tr>
<td><strong>Monitor</strong></td>
<td></td>
</tr>
<tr>
<td>Try, check, revise</td>
<td>Cooper &amp; Sandi-Urena (2009), Hartman (2001a), Howard et al. (2000), Resnick &amp; Glaser (1976), Schraw (2001)</td>
</tr>
<tr>
<td><strong>Evaluate</strong></td>
<td></td>
</tr>
<tr>
<td>Answering the question</td>
<td>Cooper &amp; Sandi-Urena (2009), Resnick &amp; Glaser (1976), Schraw (2001)</td>
</tr>
<tr>
<td>Checking the answer</td>
<td>Cooper &amp; Sandi-Urena (2009), Hartman (2001a), Howard et al. (2000), Polya (1957), Resnick &amp; Glaser (1976)</td>
</tr>
<tr>
<td><strong>New Knowledge</strong></td>
<td></td>
</tr>
<tr>
<td>What new things have I learned while doing this question?</td>
<td>Baird (1986), Polya (1957)</td>
</tr>
</tbody>
</table>
TAPPS protocol provided students with a collaborative problem solving experience. One student (i.e., the problem solver) described their thinking while solving the problem. Their partner (i.e., the listener) helped to draw out more details about the problem solver’s process. Encouraging the students to articulate their thoughts improved their awareness of their thinking while problem solving and provided an opportunity for students to practice their metacognitive skills (Hartman, 2001a).

Lastly, the students completed two design labs during the intervention: The Determination of the Formula for a Hydrate (DL-3) and Measuring the Composition of Eggshells (DL-4). DL-3 (Hydrate) appears in Appendix C and DL-4 (Egg) appears in Appendix D. Both labs were presented to the students on a handout with the metacognitive checklist on it. These activities gave students another opportunity to practice applying the Metacognitive Framework. My informal observations of students participating in design lab activities during other chemistry classes revealed that these activities create an opportunity for students to become more aware of their thinking.

Design labs are collaborative activities during which students explain their thinking to their partner, compare approaches, and reach agreement on a plan for the procedure. In the moment monitoring happens when students need to adjust their procedure in response to how the experiment is progressing.

**Data Sources**

Five data types were used during this study: (a) the Metacognitive Activities Inventory (MCAI), (b) pre- and post-test Problem Solving Tasks (PSTs), (c) TAPPS
protocols, (d) pre- and post-test design lab reports, (e) a survey of the students’ experiences with the Metacognitive Framework during the intervention period, and (f) the exit interview with the participating teacher. Three of these data sources employed problem solving activities: the PSTs, TAPPS protocols, and design labs. Pen and paper problems were selected for pre- and post-test PSTs, and the two TAPPS protocols. A different problem was presented to the students for each of the four events. The problems selected for the PSTs and think aloud protocols included complex stoichiometry problems. For the design labs, problems were selected that required the students to design an experiment, collect data, analyze data to solve the problem, draw a conclusion, and evaluate their procedure. All problem solving activities required students to apply and build on concepts they had been introduced to during class. The design and selection of all problems used for the PSTs, TAPPS protocols, and design labs took place in consultation with experienced high school and university chemistry instructors. I field tested all of these problems with chemistry students I taught prior to beginning the study. In the sections that follow, I describe each type of data source in more detail.

**MCAI**

The students’ metacognitive skillfulness was measured by the Metacognitive Activities Inventory (MCAI) (Cooper & Sandi-Urena, 2009; Appendix E). The inventory consists of 27 items and uses a 5-point Likert Scale ranging from 1, *strongly disagree* through 5, *strongly agree*. The internal consistency of the MCAI produced Cronbach’s α values ≥ 0.85 (Cooper & Sandi-Urena, 2009). Cooper and Sandi-Urena (2009) scored
responses to the instrument as a percentage total score with a higher percentage score corresponding to higher metacognitive skillfulness. In my study, students’ responses to the instrument were scored by adding together the total number of points to a maximum of 135.

**PST**

Students’ problem solving abilities were measured using pre- and post-test forms of the Problem Solving Task (PST). The pre-test problem is an adaptation of a problem designed by Mei-Jung Yang at the Centre for Science Education, University of Glasgow (Reid & Yang, 2002a). The structures for ozone shown in the pre-test problem were proposed by Hoffmann (2004). I designed the post-test PST using data provided by Fulhage, Sievers, and Fischer (1993). The pre-test PST appears in Appendix F, and the post-test PST appears in Appendix G.

I graded the pre- and post-test PSTs using two different methods: a rubric (see Appendix H), and a mark scheme out of 17 points. The mark scheme included 14 points for the correctness of the solution and 3 points for the communication of the solution (units of measurement, organization, and clarity). Five papers representative of high, medium, and low achievement for each of the two PSTs were selected for the purpose of moderation. Moderation is an assessment process in which teachers meet with each other to discuss and review their application of the assessment criteria used to assess students’ performance (Ontario Ministry of Education, 2007). These papers were graded using the rubric and mark scheme by two other chemistry teachers to check for consistency with
my grading, and to provide feedback to me about the two methods for marking the PSTs. Both teachers preferred the mark scheme to the rubric for assessing the problems. They independently reported three disadvantages of the rubric. First, the rubric was too subjective for the types of tasks used in the PSTs. Second, the rubric descriptors were not sensitive enough to sufficiently differentiate between the levels of student achievement. Third, the rubric was time consuming to use. It required teachers to consult with each other to select and reach consensus on anchor papers representative of each level of ability. Based on this feedback, I used the grades determined by the mark scheme for the analysis of the PSTs.

**TAPPS Protocols**

TAPPS protocols (Hartman, 2001a; Whimbey & Lochhead, 1986) occurred on two occasions: once near the beginning of the intervention, and once towards the end of the intervention (see Appendices I and J). All students in the study group completed the TAPPS protocols; however, only four pairs of students were randomly selected to be audio recorded. Both problems were adapted from past questions on the International Baccalaureate Higher Level Chemistry exams (International Baccalaureate Organization, 2006). The think aloud protocol was integrated into the problem solving activity with the goal of capturing the students’ natural problem solving behaviours. During these events, each member of the pair assumed the role of either the problem solver or the listener. The problem solver was instructed to verbalize all thinking at each stage of the problem solving process. The listener was instructed to think along with the problem solver, to
encourage the problem solver to continue to articulate his or her thoughts, to request clarification at any point if needed, to check the work of the problem solver, and to point out errors to the problem solver. The students switched roles as the problem solver or listener for the second TAPPS protocol.

**Design Labs**

The students completed four design labs during the semester titled: Investigating the Density of an Apple (DL-1), The Great Oreo Investigation (DL-2), Determination of a Formula of a Hydrate (DL-3), and Measuring the Composition of Eggshells (DL-4). The first design lab, DL-1 (Apple) was a formative exercise for students to practice elements of a design lab and to become familiar with the teacher’s expectations for lab reports. The elements selected were drawn from the International Baccalaureate internal assessment criteria for all the experimental sciences (International Baccalaureate Organization, 2007). These criteria are: (a) formulating a specific purpose, b) identifying the variables (independent and dependent) and controls, c) devising a procedure for which sufficient data can be collected, d) analyzing the data, e) drawing conclusions, f) evaluating the procedure, and g) suggesting ways to improve the procedure. DL-2 (Oreo) was selected as a pre-test event because it occurred before the Metacognitive Framework was introduced (see Appendix K). DL-3 (Hydrate) and DL-4 (Egg) were completed during the intervention. Both labs are adaptations of experiments presented by Lechtanski (2000). DL-4 (Egg) was selected as a post-test event because it took place at the end of
the intervention period. The students’ reports for the pre- and post-test labs provided evidence of the students’ problem solving in the lab setting.

**Exit Interview with the Participating Teacher**

I conducted a semi-structured interview with the participating teacher one week after the intervention ended. The purpose of the interview was to gain insight into the teacher’s experience with implementing the metacognitive instructional strategies, and to hear her perspective on how the students responded to these strategies. The guiding questions for the interview appear in Appendix L.

**Survey of the Students’ Use of the Framework**

At the end of the intervention, I surveyed the students to find out how useful they found the Metacognitive Framework as a model for problem solving. The students were asked to rate the overall usefulness of the model on a 1 to 5 visual analog scale with 5 being *very useful* and 1 being *not useful at all*. The students were asked to write comments about their overall experience using the model, to identify the part of the model they found most useful, and to identify the part of the model they found least useful. The survey appears in Appendix M.

**Procedure**

In the semester prior to my study, the pre- and post-test PSTs were used in conjunction with the MCAI with the pilot group. The students’ responses to these problems were used as group data to field test the instruments to be used and also to provide a baseline measure of the type of growth and learning that occurs in the absence
of the intervention. In this regard, these group data collected as part of the regular teaching process during that semester provided a baseline control for my research.

Prior to beginning my actual study, approval was sought from the teacher of the study group, the school principal, and the Director of Education for the school board. Ethical clearance from Queen’s University General Research Ethics Board was also obtained. A Letter of Information was sent to the parents or guardians (see Appendix N), students (see Appendix O), and teacher (see Appendix P). Implicit consent was sought from parents through the Letter of Information and by an automated phone message distributed through the school’s Centre Voice system. Explicit consent was obtained from the teacher and students through a signed Consent Form. All students in the class consented to participate in the study. This study was designed to minimize disruption to the routine learning environment. The PSTs, TAPPS protocols, and design labs were presented to the students as in class problem solving activities. Data collection began in the second semester of the 2009-2010 school year. The students were randomly assigned an element name from the Periodic Table as an identification code at the start of the study. The use of element names protected the confidentiality of the students who participated in the study. As the researcher, I maintained an electronic record of the code names on a password protected computer for the duration of the study. The teacher was also given the pseudonym, Chlora, to protect her confidentiality.

The sequence of events that occurred during the study is shown in Table 6. After obtaining consent forms from the teacher and students, I delivered and supervised Events
A, B, C, G, I, J, and K. Throughout these events, the students were allowed to use their class notebooks, Periodic Table, and calculators. To help ensure a complete set of data, daily attendance records were consulted, and each data collection event occurred on a day when all students were present. This flexibility was possible because I work in the same school as the participating teacher. In addition, both of us were assigned complementary schedules that allowed me to lead data collection with the study group while the participating teacher instructed my Grade 11 class using the same problem solving tasks. While I visited the study group to observe Chlora’s implementation of the intervention, a colleague supervised the students in my Grade 11 class. All problem solving tasks used in the study were a part of normal instructional content for the Grade 11 courses. Overall, there was minimal disruption to the learning in either class due to the study.

In Event A, a pre-determination of students’ metacognitive skill use and their problem solving abilities were measured using the MCAI questionnaire within the context of working on the pre-test PST. This event took place during one 73-minute class period at the end of the first unit of study (i.e., Chemical Reactions). At the beginning of the class, I provided instructions to the students for completing the tasks. Both the PST and MCAI were distributed at the same time. The students were given five minutes of reading time at the start of each task and were instructed not to write anything during this period. After the reading time, a brief think aloud protocol was incorporated into the problem solving task. The students were instructed to consult with a partner to discuss possible strategies to approach the problem before each student embarked upon their
individual solution to the problem. The students were allowed to make written notes at this time. After this think aloud period, the students separated from their partners. The students were then given 40 minutes to work on an individual response to the problem and to complete the MCAI. I chose to administer the MCAI and the PST at the same time to help students connect their use of metacognitive skills to their problem solving processes. I collected the students’ responses to the MCAI and PST.

The implementation of the intervention began at the start of the second unit of study (i.e., Quantities in Chemical Reactions) and proceeded for the next 10 weeks. Near the beginning of the intervention, Event C, a TAPPS protocol, took place. I described the event to the students, with a description of the roles for the problem solver and listener. A copy of the guidelines for the TAPPS protocol appears in Appendix Q. The event took approximately 45 minutes. The students were instructed to select a partner of the opposite sex. This was done to facilitate the recognition of each member of the pair during the transcription of the audio recordings. I randomly selected the pairs to be audio recorded by drawing four element codes names from a beaker. The entire session was audio recorded for the four selected pairs of students. The students’ solutions to this problem were collected to assist me with the analyses of these data.
Table 6

Sequence of Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Description of the Event</th>
<th>Code</th>
<th>Occurrence of the Event</th>
<th>Research Question Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Pre-test MCAI and PST</td>
<td></td>
<td>Day 1 of the study</td>
<td>1 and 2</td>
</tr>
<tr>
<td>B</td>
<td>The Introduction of the Metacognitive Framework and first observation of the class</td>
<td></td>
<td>Day 1 of the intervention</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>First TAPPS Protocol</td>
<td>T1</td>
<td>Week 3 of the intervention</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>Design Lab – Determination of the Formula for a Hydrate</td>
<td>DL-3</td>
<td>Week 4 of the intervention</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Second observation of the class</td>
<td></td>
<td>Week 5 of the intervention</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Third observation of the class</td>
<td></td>
<td>Week 6 of the intervention</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Second TAPPS Protocol</td>
<td>T2</td>
<td>Week 7 of the intervention</td>
<td>3</td>
</tr>
<tr>
<td>H</td>
<td>Design Lab – Measuring the Composition of Eggshells</td>
<td>DL-4</td>
<td>Week 9 of the intervention</td>
<td>2</td>
</tr>
<tr>
<td>I</td>
<td>Post-test PST and MCAI</td>
<td></td>
<td>Week 10 of the intervention</td>
<td>1 and 2</td>
</tr>
<tr>
<td>J</td>
<td>Survey of the Students’ Use of the Metacognitive Framework</td>
<td>SF</td>
<td>Week 10 of the intervention</td>
<td>4</td>
</tr>
<tr>
<td>K</td>
<td>Exit interview with Chlora</td>
<td></td>
<td>One week after the intervention ended</td>
<td>2 and 4</td>
</tr>
</tbody>
</table>

Note. I devised a coding system to connect the data to the event and source. Letters were used to describe the type of data collecting event. A number followed this if the type of event happened more than once. Within the text, this code was followed by the code name for the participant who contributed the data. For example, T1, Iron represents a comment made in the first TAPPS Protocol by Iron.
Later in the intervention period, Event G, a second TAPPS protocol was conducted. The format and duration for both Events C and G were the same. For the second TAPPS protocol, the pairs switched roles; the problem solver in the first session became the listener in the second session and vice versa. The same pairs were recorded for both events to allow the linking of data.

The students completed two design labs, DL-3 (Hydrate, Event D) and DL-4 (Egg, Event H), during the intervention. Both design labs were presented to the students on a hand-out that included the metacognitive checklist adapted for inquiry activities (see Appendix B). During a class prior to the hydrate lab (DL-3), the students completed an example problem in which the teacher provided sample lab data and guiding questions to lead them through the analysis of the sample data. The students were then required to design an experiment to collect their own data for the determination of the formula for a different unknown hydrate. The students were given less direction from Chlora for the egg lab (DL-4). For this lab, the students were provided with background information about the composition of eggshells and a chemical reaction relevant to the experiment. The students were required to come up with their own independent and dependent variables, procedure, and method of analysis.

I observed the study group three times during the intervention period. During the first classroom visit (Event B), I observed Chlora’s introduction of the Metacognitive Framework to the students. On two subsequent visits, I observed Chlora introduce
limiting reactant problems (Event E) and titration problems (Event F) using the Metacognitive Framework as a model for problem solving.

At the end of the intervention, the students’ reported use of metacognitive skills and their problem solving abilities were measured using the MCAI questionnaire within the context of working on the post-test PST (Event I). The format and duration for the post-test event was the same as for the pre-test (Event A). After the completion of the post-test MCAI and PST, I surveyed the students about how useful they found the Metacognitive Framework as a model problem solving (Event J).

I concluded the study with the exit interview with Chlora (Event K). The interview took place after classes in my office. The interview was audio recorded and lasted about 45 minutes.

**Analyses**

Descriptive and inferential statistics were used to analyze the pre- and post-test MCAI and PST scores. These analyses were completed for data collected from the pilot and study groups. The transcripts for the TAPPS protocols, the transcript of the exit interview with Chlora, the students’ pre- and post-test design lab reports, and the students’ responses to the survey of their use of the Metacognitive Framework were analyzed using qualitative methods. These analyses were completed for only the study group.
**Statistical Analyses**

SPSS (version 17.0) was used to examine the MCAI and PST data. These data were checked for accuracy of data entry, missing values, and the degree to which the distributions met the assumption of normality. Descriptive statistics (n, M, SD, skewness and kurtosis) were calculated for all administrations of the MCAI and PST. Cronbach’s alpha was calculated to test the internal consistency of the MCAI. An alpha level of 0.05 was used for all statistical tests that followed. One way repeated measures analysis of variance (ANOVA) was completed to determine if the mean scores for the pre- and post-test MCAI were significantly different within and between the pilot and study groups. These analyses addressed the first research question intended to determine the effect of purposeful metacognitive instruction on students’ use of metacognitive skills.

One way repeated measures analysis of variance (ANOVA) was completed to determine whether the mean scores for the pre- and post-test PSTs were significantly different within and between the pilot and study groups. These analyses addressed the second research question intended to determine the effect of purposeful metacognitive instruction on students’ abilities to solve chemistry problems.

In addition, achievement groups within the study group were examined. Two achievement groups of equal size (n=9) were formed based on their final Grade 11 chemistry grades. Students in the higher achievement group attained a final grade of 83% or higher, students in the lower achievement group attained a final grade of 75% or lower, and the three students with grades between these bands were removed from the
data set. My determination of the mark boundaries for the achievement groups was guided by my goal to make two distinct groups of equal size with minimal reduction in the sample size. These mark boundaries approximately align with The Ontario Achievement Chart (Ontario Ministry of Education, 2008); achievement above 80% exceeds the Provincial standard and achievement below 70% does not meet the Provincial standard. One way repeated measures analysis of variance (ANOVA) was performed to determine whether a significant difference between the means on the pre- and post-test MCAI existed within and between the subjects. These analyses were repeated using the mean scores on the pre- and post-test PST in place of the pre- and post-test mean MCAI scores.

**Qualitative Analyses**

**TAPPS Protocols.**

Verbatim transcriptions of the audio recorded TAPPS protocols were completed for four pairs of students for both sessions (Events C and G). My analyses of the transcripts were guided by the coding, seeking patterns, and theme analysis methods described by Patton (2002). Initially, I read the transcripts to gain an understanding of the students’ approaches to solving the problem. I then reread the transcripts and highlighted segments of text that exemplified the metacognitive skills associated with planning, monitoring, and evaluation. I coded the segments of text using planning, monitoring and evaluation as a priori codes. The description of the kinds of skills I looked for as planning, monitoring, and evaluation appear in Table 7. I provided Chlora with a
photocopy of a sample from the transcripts selected equally from each pair of students for both events. I asked Chlora to code the transcript samples as a way to check the reliability of my coding. I then compared my coding with how Chlora coded the sample. I discussed the discrepancies with Chlora. This dialogue contributed to my understanding of the coding and how it applied to what the students were saying.

The process of establishing the coded data was an iterative process. To assist me to better follow the students’ verbalizations, I referred to photocopies of the participants’ written solutions to the problem. I reread the transcripts in conjunction with examining their written solutions numerous times over the course of three months. Each time, my grasp of their problem solving process was enriched. I concluded this process when my coding of the transcripts stabilized. For the next phase of my analyses, I created a Microsoft Excel spreadsheet with the column headings: Code Name of Student, Event, Comment, Metacognitive Skill Code, and Keyword. I transferred these data to the spreadsheet. Filters for each column were used to extract subsets of the data. For example, I could generate a short list of comments I coded as monitoring. My examination of the data subsets revealed themes within each metacognitive skill code, and a theme code was added as a new filterable column. By continuing to use the spreadsheet filters, I was able to gain a clearer picture of these data. These analyses addressed the third research question intended to determine how students use metacognitive skills during problem solving.
Table 7

*Coding for the TAPPS Protocols*

<table>
<thead>
<tr>
<th>Metacognitive Skill Code</th>
<th>Description of Skills to Look For</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Connection to previous learning</td>
</tr>
<tr>
<td></td>
<td>Identification of the goal</td>
</tr>
<tr>
<td></td>
<td>Sorting useful information</td>
</tr>
<tr>
<td></td>
<td>Breaking down the problem into steps</td>
</tr>
<tr>
<td></td>
<td>Finding relations between the variables</td>
</tr>
<tr>
<td></td>
<td>Mapping a solution</td>
</tr>
<tr>
<td></td>
<td>Using heuristics</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Checking at various stages</td>
</tr>
<tr>
<td></td>
<td>Seeking clarification from partner</td>
</tr>
<tr>
<td></td>
<td>Pointing out errors</td>
</tr>
<tr>
<td></td>
<td>Justification of actions</td>
</tr>
<tr>
<td></td>
<td>Correcting wrong turns</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Checking the final answer</td>
</tr>
<tr>
<td></td>
<td>Verifying that the solution answers the question</td>
</tr>
<tr>
<td></td>
<td>Acknowledgement of new learning</td>
</tr>
</tbody>
</table>

**Exit Interview with Chlora.**

A verbatim transcription of the exit interview with Chlora was completed. I met with Chlora to have her review the transcript as a Microsoft Word file. I invited her to make corrections, clarify parts of her responses, and make any additional comments she wanted to include in the interview. I then read the cleaned transcript to gain an overall sense of what Chlora wanted to share about her experience with implementing the intervention with her students. Initially, I highlighted sections of the transcript that revealed meaningful points relating to my research questions, Chlora’s experience with
the intervention, and her insights into students’ problem solving behaviours. My analysis of the transcript was guided by the inductive approach described by Boyatzis (1998) and Thomas (2006). I wrote descriptive phrases in the margin of the document beside the highlighted sections. For example: “students’ use of the framework,” “incorporating design labs,” and “lab to theory disconnect.” I sought commonalities between the highlighted sections. This was an iterative process that eventually guided me to combine the descriptive codes that shared commonalities into three codes: “Value of Framework,” “Role of Design Labs,” and “Instructional Implications.” I then clustered the key segments from the transcripts under each code as a heading and searched for themes. Data obtained from the exit interview with Chlora contributed to the second research question intended to determine the effect of purposeful metacognitive instruction on students’ abilities to solve chemistry problems. These data also addressed the fourth research question intended to determine how students used the Metacognitive Framework as a model for problem solving. Lastly, data from the exit interview prompted me to examine design labs as a source of data.

**Design Lab Reports.**

The class set of lab reports for all the design labs completed during the semester were converted to Adobe Acrobat files. I selected the students’ DL-2 (Oreo) and DL-4 (Egg) as the pre- and post-test sample. Using a pdf mark-up program called PDF-Viewer, I colour highlighted key sections of the reports and coded these data with respect to the metacognitive skills associated with planning, monitoring, and evaluation. The
description of the kinds of skills that represented planning, monitoring, and evaluation appears in Table 8. Next, for individual students, I reexamined the lab report for DL-2 (Oreo) and DL-4 (Egg) sequentially; I noted changes in the degree to which the student incorporated planning, monitoring, and evaluation skills in the lab reports. I kept track of these data in a word processing file that contained verbatim excerpts from the reports, the coding of these excerpts, and side by side excerpts to compare the students’ reporting for DL-2 (Oreo) and DL-4 (Egg). Data obtained from the design lab reports were used to address the second research question intended to determine the effect of purposeful metacognitive instruction on students’ abilities to solve chemistry problems.

Table 8

*Coding for the Design Lab Reports*

<table>
<thead>
<tr>
<th>Problem Solving Model Code</th>
<th>Description of Skills to Look For</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Addressing the goal</td>
</tr>
<tr>
<td></td>
<td>Identifying independent, dependent, and control variables</td>
</tr>
<tr>
<td></td>
<td>The Procedure allows for the collection of sufficient, and relevant data</td>
</tr>
<tr>
<td></td>
<td>An outline of the data analysis is described</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Realization of procedural flaws at the bench</td>
</tr>
<tr>
<td></td>
<td>On the fly procedural changes</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Data analysis matches the goal.</td>
</tr>
<tr>
<td></td>
<td>Identifying limitations of the design</td>
</tr>
<tr>
<td></td>
<td>Suggesting procedural revisions</td>
</tr>
<tr>
<td></td>
<td>Explaining the direction of the error</td>
</tr>
<tr>
<td></td>
<td>Reporting new learning gained</td>
</tr>
</tbody>
</table>
Survey of the Students’ Use of the Metacognitive Framework.

Finally, I surveyed the students about their use of the Metacognitive Framework. First, I determined the number of students who selected each overall rating category from 5 (very useful) to 1 (not useful at all) to gain a sense of how useful the students found the Metacognitive Framework while they worked through problems. Next, I examined their comments from the three questions that elicited qualitative responses about the overall usefulness of the Framework, the aspect of the Framework they found most useful, and the aspect of the Framework they found least useful. I created a spreadsheet in Microsoft Excel with the column headings: Student’s Code Name, Overall Rating of the Model, Overall Comments, Most Useful Part of the Model, Least Useful part of the Model, and Code. I copied the students’ comments to the spreadsheet. I coded their comments using the main categories from the Metacognitive Framework as the codes: current knowledge, planning, monitoring, evaluation, and new knowledge. Then, I applied the filtering technique used in the analysis of the TAPPS protocols. After my initial examination of these data, I added column in which I recorded the achievement group for each student. By applying filters, I was able to view subsets of these data. Trends in the way students’ from the different achievement groups used the framework became apparent. These survey data addressed the fourth research question intended to determine if the Metacognitive Framework provided a useful model for problem solving.
CHAPTER 4
RESULTS AND ANALYSES

The intent of this study was to explore students’ use of metacognitive skills during problem solving activities and to determine how explicit metacognitive instruction affects their use of metacognitive skills and their problem solving abilities. I collected data using a variety of methods to address four related research questions. Statistical analyses were conducted with the pre- and post-test scores on the Metacognitive Activities Inventory (MCAI) and Problem Solving Tasks (PSTs) collected for the pilot and study groups. For the analyses of these data, the study group was further divided into two equal groups based on their final Grade 11 chemistry course grades: the higher achievement group scored 83% or higher, and the lower achievement group scored 75% or lower.

There were 26 students in the pilot group and 21 students in the study group. All students in the study group completed the pre- and post-test PSTs. However, these data were not complete for the pilot group. To attain maximum power, I used the maximum sample size available for each analysis. Hence the sample varied from 18 to 26 students for the pilot group.

I completed additional analyses on data obtained through two audio recorded think aloud pair problem solving protocols (TAPPS), an exit interview with the classroom teacher, the students’ written reports for The Great Oreo Investigation (DL-2) and Measuring the Composition of Eggshells (DL-4), and the survey of the students’ use
of the Metacognitive Framework at the end of the intervention. These data were collected for only the study group. These analyses are reported in four parts organized by data source and research question.

**The Effect of Metacognitive Instruction on Students’ Use of Metacognitive Skills**

My first research question was to determine the effect of purposeful metacognitive instruction on students’ use of metacognitive skills. To address this question, I analyzed students’ scores on the pre- and post-test MCAI within each group and between the groups. The MCAI consists of 27 items that use a 5-point Likert scale. Scores on the pre- and post-test MCAI were obtained by adding together the points selected by the student for each item on the questionnaire to a maximum possible total of 135 points. Eight items on the MCAI are negatively worded, and the responses for these items were reverse coded before any analysis was completed.

Descriptive statistics, (i.e., n, M, SD, minimum and maximum values, skewness, and kurtosis) for the pre- and post-test MCAI appear in Table 9. The means and standard deviations on both measures were observed to be higher for the study group compared to the pilot group. The significance of this was determined in subsequent analyses. The range in scores on the pre- and post-test MCAI was greater for the study group. The skewness and kurtosis indices describe how well the data match a normal distribution. For the pilot group, the post-test MCAI was significantly positively skewed, indicating that students tended to have similar scores at the lower end of the distribution and that these data do not match a normal distribution.
### Table 9

*Descriptive Statistics for the MCAI*

<table>
<thead>
<tr>
<th>Group</th>
<th>Measure</th>
<th>n</th>
<th>M</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
<th>alpha</th>
<th>Cronbach’s</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pilot</strong></td>
<td>Pre-test MCAI</td>
<td>22</td>
<td>94.00</td>
<td>10.36</td>
<td>77.0</td>
<td>114.5</td>
<td>0.76</td>
<td>N/A</td>
<td>-0.03</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Post-test MCAI</td>
<td>21</td>
<td>95.85</td>
<td>11.47</td>
<td>82.0</td>
<td>125.0</td>
<td>0.85</td>
<td></td>
<td>1.04</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Study</strong></td>
<td>Pre-test MCAI</td>
<td>21</td>
<td>100.0</td>
<td>12.54</td>
<td>75.0</td>
<td>121.0</td>
<td>0.87</td>
<td></td>
<td>-0.37</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Post-test MCAI</td>
<td>21</td>
<td>101.5</td>
<td>11.73</td>
<td>71.0</td>
<td>118.0</td>
<td>0.86</td>
<td></td>
<td>-0.88</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Lower</strong></td>
<td>Pre-test MCAI</td>
<td>9</td>
<td>98.56</td>
<td>13.68</td>
<td>75.0</td>
<td>120.0</td>
<td>--</td>
<td></td>
<td>-0.37</td>
<td>0.72</td>
</tr>
<tr>
<td>Achievement*a</td>
<td>Post-test MCAI</td>
<td>9</td>
<td>97.56</td>
<td>8.65</td>
<td>83.0</td>
<td>112.0</td>
<td>--</td>
<td></td>
<td>-0.084</td>
<td>0.72</td>
</tr>
<tr>
<td><strong>Higher</strong></td>
<td>Pre-test MCAI</td>
<td>9</td>
<td>101.44</td>
<td>11.68</td>
<td>77.0</td>
<td>121.0</td>
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<td></td>
<td>-0.70</td>
<td>0.72</td>
</tr>
<tr>
<td>Achievement*a</td>
<td>Post-test MCAI</td>
<td>9</td>
<td>109.00</td>
<td>8.03</td>
<td>91.0</td>
<td>118.0</td>
<td>--</td>
<td></td>
<td>-1.50</td>
<td>0.72</td>
</tr>
</tbody>
</table>

*a Subgroup of the Study group*
The internal consistency of the MCAI was tested using Cronbach’s alpha. An alpha value above 0.70 indicates that the results of an instrument are consistent and reproducible (Cooper & Sandi-Urena, 2009). Both administrations of the MCAI provided evidence of sufficient internal consistency with alpha ranging from 0.76 to 0.87.

Statistically significant positive correlations were found between the pre- and post-test MCAI for the both the pilot and study groups ($p < 0.05$). With a correlation of 0.58, 34% of the variance was shared between these two measures within the pilot group. For the study group, the correlation was 0.67 indicating that 45% of the variance was shared between the pre- and post-test MCAI. These results indicate that the association between students’ metacognition scores on the pre- to post-test was similar for both the pilot and study groups.

One way repeated measures analysis of variance (ANOVA) was conducted to determine if there were any differences across the pre- and post-test MCAI for the pilot and study groups. Only those students who completed both the pre- and post-test MCAI were included in these analyses, resulting in a sample of 18 students in the pilot group and 21 students in the study group. The results for the within subjects ANOVA indicate that the pre- and post-test MCAI scores were not significantly different, $F(1,37) = 3.31, p > 0.05$. The between subjects results indicated that the pilot and study groups did not differ significantly on the mean scores for pre- and post-test MCAI, $F(1,37) = 3.18, p > 0.05$. Lastly, there was no interaction between group and MCAI score, $F(1,37) = 0.83, p > 0.05$. These results suggest that both the pilot and study groups had similar scores on
the MCAI throughout, and that the teaching intervention implemented for the study group did not appear to alter students’ use of metacognitive skills as measured by the MCAI.

Given the lack of significant findings, I looked at individual student responses to the MCAI questionnaire. I noticed that one student in the study group was confused by the eight items that were negatively worded. Further examination of the student responses to these items showed that others may have also misinterpreted these items. Previous research has also noted students’ difficulty in interpreting negatively worded items (Schmitt & Stuits, 1985). The potential for students to misread negatively worded items is worthy of further consideration in studies that make use of the MCAI. Nevertheless, a second set of analysis with these items removed did not significantly change the overall findings for this study.

The effect of metacognitive instruction on students’ use of metacognitive skills was investigated further for the achievement subgroups of the study group. Descriptive statistics, (i.e., n, M, SD, minimum and maximum values, skewness, and kurtosis) for the pre- and post-test MCAI appear in Table 9. The pre- and post-test MCAI scores were observed to be higher for the higher achievement group, and the significance of this was tested in later analyses. The standard deviation of the means scores on the MCAI was lower for the higher achievement group and decreased from the pre- to post-test MCAI for both groups. For both the higher and lower achievement groups, the range in means was greater for the pre-test MCAI compared to the post-test MCAI. Both the pre- and
post-test MCAI scores for the higher achievement group were found to have significant positive kurtosis indicating a narrow (i.e., leptokurtic) distribution of scores.

One way repeated measures analysis of variance (ANOVA) was completed to investigate the mean scores on the MCAI for the achievement groups. The results for the within subjects ANOVA indicated that the pre- and post-test MCAI scores were not significantly different, \( F(1,16) = 4.25, p > 0.05 \). The between subjects ANOVA indicated that higher and lower achievement groups did not differ significantly on the pre- and post-test MCAI scores, \( F(1,16) = 2.21, p > 0.05 \). However, there was a significant group interaction, \( F(1,16) = 7.24, p < 0.05 \) indicating that the MCAI scores diverged for the higher and lower achievement groups. The mean scores for the higher achievement group increased while mean scores for the lower achievement group decreased over time (see Figure 2). These results suggest that the intervention may have a differential effect for the students based on their overall level of achievement in the Grade 11 chemistry course.

Figure 2. Mean Scores on the MCAI for the Achievement Groups
The Effect of Metacognitive Instruction on Students’ Abilities to Solve Chemistry Problems

My second research question was to determine the effect of purposeful metacognitive instruction on students’ abilities to solve chemistry problems. To address this question, I used three analyses: (a) the students’ scores on the pre- and post-test PST were analyzed within each group and between the groups, (b) the exit interview with Chlora was analyzed for evidence of students’ problem solving process, and (c) the students’ lab reports for two design labs were analyzed for evidence of the students’ change in problem solving over the semester. The design lab reports enabled me to explore students’ uses of the metacognitive categories (i.e., planning, monitoring, and evaluation) and provided a mechanism to examine evidence of scientific thinking.

PST

Each of the pre- and post-test problem solving tasks was marked using a mark scheme out of a maximum of 17 points. Descriptive statistics, (i.e., n, M, SD, minimum and maximum values, skewness, and kurtosis) for the pre- and post-test PST appear in Table 10. The means and standard deviations on both measures were observed to be higher for the study group compared to the pilot group. For both groups, the mean for the post-test was observed to be higher than the mean for the pre-test. The significance of these observed differences were investigated in subsequent analyses. For both groups the standard deviation increased from the pre- to post-test PST. The observed range in the means for post-test PST was greater for the pilot group than the study group. The data for
both tests and groups matched a normal distribution since neither the skewness nor the kurtosis was significant.

No significant correlation was found between the pre- and post-test PST scores for the pilot group. A statistically significant positive correlation was found between the pre- and post-test PST scores for the study group. With a correlation of 0.59, 35% of the variance was shared between these two measures within the study group. These results indicate that the students’ problem solving abilities changes somewhat equally from the pre- to post-test events for the study group.

One way repeated measures analysis of variance (ANOVA) was conducted to determine if there were any differences across the pre- and post-test PSTs for the pilot and study groups. Only those students who completed both the pre- and post-test PSTs were included in these analyses, resulting in a sample of 21 students in the pilot group and 21 students in the study group. The results for the within subjects ANOVA indicated that the post-test PST scores were significantly higher than the pre-test scores, $F(1,40) = 31.42, p < 0.05$. The between subjects results indicated that the pilot and study groups differed significantly on the mean scores for pre- and post-test PST, $F(1,40) = 4.52, p < 0.05$. Lastly, there was no interaction between group and PST score, $F(1,40) = 0.058, p > 0.05$. These results suggest that students’ problem solving abilities improved over the semester for both groups. The exposure of the study group to metacognitive instructional strategies did not significantly alter their abilities to solve problems.
Table 10

*Descriptive Statistics for the PST*

<table>
<thead>
<tr>
<th>Group</th>
<th>Measure</th>
<th>$n$</th>
<th>$M$</th>
<th>$SD$</th>
<th>Min</th>
<th>Max</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\gamma_1$</td>
<td>$SE$</td>
</tr>
<tr>
<td>Pilot</td>
<td>Pre-test PST</td>
<td>26</td>
<td>4.92</td>
<td>2.21</td>
<td>0</td>
<td>9</td>
<td>-0.26</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Post-test PST</td>
<td>21</td>
<td>9.38</td>
<td>4.69</td>
<td>3</td>
<td>17</td>
<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
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<td>Pre-test PST</td>
<td>21</td>
<td>7.81</td>
<td>4.07</td>
<td>1</td>
<td>15</td>
<td>-0.10</td>
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<td>Post-test PST</td>
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<td>11.52</td>
<td>5.23</td>
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<td>0.50</td>
</tr>
<tr>
<td>Lower</td>
<td>Pre-test PST</td>
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<td>5.56</td>
<td>3.78</td>
<td>1</td>
<td>12</td>
<td>0.48</td>
<td>0.72</td>
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<tr>
<td>Achievement$^a$</td>
<td>Post-test PST</td>
<td>9</td>
<td>8.78</td>
<td>5.14</td>
<td>3</td>
<td>16</td>
<td>0.65</td>
<td>0.72</td>
</tr>
<tr>
<td>Higher</td>
<td>Pre-test PST</td>
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<td>9.89</td>
<td>3.86</td>
<td>2</td>
<td>15</td>
<td>-0.65</td>
<td>0.72</td>
</tr>
<tr>
<td>Achievement$^a$</td>
<td>Post-test PST</td>
<td>9</td>
<td>14.33</td>
<td>4.80</td>
<td>2</td>
<td>17</td>
<td>-2.63</td>
<td>0.72</td>
</tr>
</tbody>
</table>

$^a$Subgroup of the Study group
The effect of metacognitive instruction on students’ abilities to solve chemistry problems was investigated further for the achievement subgroups of the study group. Descriptive statistics, (i.e., n, M, SD, minimum and maximum values, skewness, and kurtosis) for the pre- and post-test PST scores appear in Table 10. The scores on the post-test PST were observed to be higher than the scores on the pre-test PST for both achievement groups. The means for the higher achievement group on both the pre- and post-test PSTs were observed to be higher than the means on the same measures for the lower achievement group. The significance of these observed differences were determined in subsequent analyses. For both groups, the standard deviation of the means increased from the pre- to post-test PST. For both groups, the range in means was greater for the post-test PST compared to the pre-test PST. For the higher achievement group, the post-test data were significantly negatively skewed indicating that the students in the higher achievement group tended to have similar scores at the higher end of the distribution. These data also exhibited significant positive kurtosis, indicating a narrow distribution of scores (i.e., leptokurtic). The significant skewness and kurtosis of the post-test scores for the higher achievement group indicates that these data strayed from a normal distribution.

One-way repeated measures analysis of variance (ANOVA) was completed to investigate mean scores on the PSTs for the achievement groups. The results for the within subjects ANOVA indicate that the pre- and post-test PST scores were significantly different, \( F(1,16) = 11.63, p < 0.05 \). The between subjects results indicated that the
students in the higher and lower achievement groups differed significantly on the pre- and post-test PST scores, $F(1,16) = 7.88, p < 0.05$. There was no interaction between the achievement group and PST, $F(1, 16) = 0.296, p > 0.05$. The results suggest that the problem solving abilities of both the higher and lower achievement groups improved over the semester with the same upward trend. There is no evidence to support a differential impact of the intervention on the problem solving abilities of the two achievement groups.

The Design Lab as Evidence of Students’ Problem Solving Process

Design labs were incorporated as part of the intervention. These design labs were inquiry activities that required the student to design their own procedure and method of analysis for the data they collected. These labs provide further information about the students’ problem solving processes. Comments made by Chlora during the semi-structured exit interview prompted me to examine the lab reports as a data source. She noted, “The lab gives really great insight into their thinking.” Further to this, she observed growth in the students’ lab reports, commenting that, “there was a dramatic change in how students approached the design of labs, [their] interpretation of the data, and their assessment of how well they answered the question [Purpose].” The Great Oreo Investigation (DL-2) was completed prior to the intervention, and provided pre-test data (see Appendix K). Measuring the Composition of Eggshells (DL-4) was completed at the end of the semester, and provided post-test data (see Appendix D). Fifteen students completed reports for both design labs.
In the first phase of my analysis, I coded the reports for evidence of planning, monitoring, and evaluation as each applies to an inquiry activity. In the second phase, I looked for development of their problem solving abilities in lab activities from the pre-post-test lab reports. These analyses provide evidence that students’ problem solving skills in the lab setting developed during the semester. I have drawn support for these findings directly from the students’ lab reports.

**Planning.**

Five out of fifteen students demonstrated an improvement in their goal awareness. Specific to this was: formulating a purpose, identifying what data were necessary to address the purpose, analyzing the data to fulfill the purpose, and finally reporting a conclusion that aligned with the purpose. I have selected the following example to illustrate this. Iron stated this purpose for DL-2 (Oreo): “To investigate the claim ‘Double Stuf,’ and determine the brand of cookie that offers the best value to the customer by comparing the ratio between the icing and wafer for the Oreo cookies in different brands” (DL-2, Iron). In this student’s observations, data regarding the taste of the cookie was recorded. Taste was not part of the purpose. In the analyses that followed, Iron did not calculate the icing to wafer ratio. He drew conclusions that were not substantiated by the analyses he conducted. He reported that the ‘Double Stuf’ cookie had about double the amount of filling in comparison to the other two brands of cookie.

Iron demonstrated a greater awareness of the goal by showing much better consistency between the purpose, procedure, data collection, analysis, and conclusion in
his report for DL-4 (Egg). His stated purpose was: “Determine the % composition by mass of the CaCO₃ in 3 different brands of egg shells” (DL-4, Iron). As part of the procedure, Iron outlined the calculations for the data analysis:

10. Subtract mass of products from mass of reactants to determine the mass of CO₂ in products because this was evaporated during the reaction.
11. Use the mass of the CO₂ to calculate the mass of CaCO₃ for each egg. (DL-4, Iron)

Iron followed this plan to correctly analyze the data collected, thereby, meeting the goal as stated in the purpose. The student wrote a concise conclusion that reported the percentage calcium carbonate in each type of egg tested.

Two other examples of students who demonstrated improvement in their goal awareness follow. Boron and Zinc stated purposes that included finding the ratio of icing to wafer. Boron did not record the data needed to fulfill this purpose. He drew a conclusion based on the taste of each cookie, a variable that he had not identified earlier in his report. Zinc collected appropriate data but neglected to calculate the ratio described in the purpose. Instead, Zinc focused on the price per cookie in her analysis and conclusion. In their reports for DL-4 (Egg), both students showed much better consistency between the purpose, procedure, data collection, analysis, and conclusion. Each student set out to determine the percent calcium carbonate in eggshells, collected the appropriate data, carried out the calculations with these data, and concisely reported the findings in the conclusion.

Another area of improvement I noted was that six of the fifteen students incorporated a plan for the data analysis as part of the procedure in their reports for DL-4
(Egg) where they had not in their reports for DL-2 (Oreo). This provides evidence that these students thought more about what data they required and how they would analyze these data.

**Monitoring.**

Evidence of monitoring in the form of students making procedural changes at the time of lab or students checking their analysis was difficult to obtain from students’ written reports. Since the lab periods were not video recorded, I was only able to gain evidence of this if the students noted the changes as part of their written reports. Three students documented changes they made to their original procedures for DL-4 (Egg). Each noted changes made after beginning the lab and realizing that the original plan was flawed. As an example, Cobalt, clearly documented the changes she made to the method while completing DL-4 (Egg):

> The original procedure stated that since the solutions in the product other than CaCO$_3$ were aqueous, and might be boiled off using a hotplate. This procedure was then considered flawed after the realization that the assumption of boiling away products was not sufficient to record any valid data. The procedure was then adapted so that the remains of the eggshell after the reaction could be filtered and measured. (DL-4, Cobalt)

Cobalt also described revisions to her calculations in the analysis section:

> During processing the data, it was wrongly assumed that the difference between the mass of the original eggshell and the eggshell remaining after the reaction gave the mass of CaCl$_2$ rather than that of CaCO$_3$. It was then realized that it couldn’t be CaCl$_2$ since the aqueous solution was disposed during the filtration. (DL-4, Cobalt)

She included both the erroneous calculations and the corrected versions in her report.
As another example, Calcium recorded the following modifications: (a) the inner membrane was removed prior to determining the initial mass of the eggshells, (b) the mixture was stirred to insure the completion of the reaction, and (c) the final mixture was separated by filtration. These procedural changes made while the students conducted the experiment reveal that the students were thinking about how their experimental design affected the quality of their data.

**Evaluation.**

Chlora noted in her exit interview that “the quality of the conclusions that I have read has dramatically improved over the semester in terms of how they evaluate their lab.” Six of the fifteen students demonstrated an improvement in their evaluation of their investigation. I will describe the three key ways the students demonstrated this. First, the students showed development from identifying weaknesses in their own manipulative skills for pre-test lab (DL-2, Oreo) to identifying procedural design flaws in the post-test lab (DL-4, Egg). Second, the students progressed from identifying errors in DL-2(Oreo) to including how an error would impact the results in DL-4 (Egg). Third, the students’ suggestions for improvements to the procedure began as adjustments to the existing procedure for DL-2 (Oreo) and developed into descriptions of alternative procedures from which the students would collect different data to address the same goal in the later lab.

I have selected excerpts from the lab reports completed by Aluminum to illustrate the first two areas of improvement. For example, in DL-2 (Oreo), Aluminum noted:
“Another weakness was the wafers for the regular Oreos and the Double Stuf Oreos could get mixed up because they have the same design. So it’s important to label them” (DL-2, Aluminum). This student exhibited better developed evaluation skills in her report for DL-4 (Egg). Here, Aluminum identified weaknesses in the procedure, “the limitations in my experimental design are that not all the membrane was removed from the shell,” and “the mixture is not stirred enough and therefore the reaction isn’t fully completed” (DL-4, Aluminum). Later, Aluminum explained the significance of these problems: “These limitations impact the results of the experiment because by membrane remaining on the egg the HCl isn’t able to react with the shell as easily” (DL-4, Aluminum).

Finally, the students progressed from making suggestions to improve steps in the procedure for the Oreo lab (DL-2) to designing different procedures to address the goal for the Egg lab (DL-4). In his report for DL-2 (Oreo), Vanadium noted an inconsistency in the mass of the wafer. He proposed the following change to the procedure to address this: “To test if it really is bad quality control, the next step would be to measure the mass of a whole bag of Oreos to see if all the Oreos weigh more that they should if there is great discrepancy among all cookies in the package” (DL-2, Vanadium). In the evaluation section of DL-4 (Egg), Vanadium noted that a weakness of his experimental design was that the residue was contaminated by some calcium chloride that remained trapped in the filter paper. To overcome this limitation, Vanadium stated, “To avoid recording the mass of CaCl₂, I would propose a completely different procedure” (DL-4, Vanadium). Vanadium then described a new procedure in detail. The alternative procedure applied his
knowledge of the titration technique. In addition, the student thoroughly outlined the
calculations for the analysis of the new data. The new analysis required Vanadium to
integrate his understanding of limiting reactant stoichiometry problems with titration
problems.

The Design Lab as a Method to Support Scientific Thinking

During the exit interview, Chlora expressed her concern that students lacked the
ability to think scientifically. Associated with this is the students’ inability to connect
what they learn during science lessons with what they explore in the lab setting. Based on
her observations of students in many different science classes over the years, Chlora
noted, “I’m not sure they [the students] appreciate or connect what they do in the lab
always with a theory that we’re learning.” More specifically, the students don’t always
appreciate “the significance of their own data and that the numbers are in some ways
relevant to the concepts” they have been studying. Chlora observed that the students
“didn’t connect the theory with the pragmatic part of science.” She did, however, point to
one specific example of a group who during the last design lab (DL-4, Egg) “thoughtfully
went through what was happening and appreciated the significance of the chemical
equation.” This pair developed a procedure that directly incorporated the concepts about
solutions that were taught in class into their procedural design.

Chlora spoke to the value of the design labs to provide students with the
opportunity to practice their scientific thinking skills. “I think that whole exploratory
problem based way of approaching things would really help us over the long term. The
eggshell lab [DL-4] is a great example of that.” She was more specific about how design labs parallel the way scientists approach real world problems. “The design labs are more open-ended. There wasn’t a recipe. They were not given a script of what do in the procedure, analysis, or discussion. They were forced to be more thoughtful.” During the design lab activities, “They have to think about how variables related to each other. They have to think about what needs to be measured to answer the question. They have to evaluate how well their data answers the purpose of the lab.”

Over the course of the semester, Chlora noted that the students’ comfort level in the lab setting improved. As their confidence increased, “they became more reflective about what they were doing.” Design labs are an instructional strategy that explicitly targets scientific thinking skills. While practicing their scientific thinking skills, students’ abilities to solve lab based problems also improved.

**Metacognitive Skills Used by Students While Problem Solving**

Two TAPPS protocols were conducted during the intervention phase of the study. The purpose of the TAPPS protocols was twofold. First, the sessions were part of the intervention by giving the students an opportunity to become more aware of their thinking while problem solving by articulating their thinking to their partner. Second, these sessions provided a source of data to address the third research question to examine the metacognitive skills students use while problem solving. The audio recordings of TAPPS protocols for the four pairs of students provided the data to address this question. During each session, one member of the pair volunteered to be the problem solver while
his or her partner assumed the role of the listener. The pairs reversed roles for the second TAPPS protocol. During both activities, I observed that all students in the class were actively engaged in discussions with their partner about their strategies to solve the problem. The students retained their focus throughout the duration of the activity, and they were persistent in their attempt to work through the problems. The transcripts of the audio recorded pairs provide additional support for this since I found only two instances where the students made comments that were off task.

I used the planning, monitoring, and evaluation metacognitive categories to guide my analyses of the students’ data. Comments from both the problem solver and listener were coded since the roles of each member of the pair were not always distinct; the roles were fluid. I begin with an overview of each type of metacognitive category. I interpreted statements that referred to the given information, goal of the problem, or selection of relevant strategies as planning. For example, “Okay so let’s write down what we know first” (T1, Lithium). Monitoring was characterized by the “in the moment” checking of their work at intermediate stages. For example, “We need to make sure it’s balanced” (T2, Lithium). Evaluation was characterized by statements about the verification of the final answer. For example, “See if the answer we get makes sense” (T1, Zinc). My analysis revealed that the students demonstrated planning and monitoring equally for both TAPPS protocols. With the exception of one pair for the first TAPPS session, all pairs made statements about the correctness of their answers.
Planning

Examination of the transcript excerpts I coded as planning revealed the following metacognitive skills: making sense of the task, extracting the given information, being aware of the goal, seeking strategies used in the past, and mapping a solution. Within some of these skills, I noted varying levels of sophistication in the way the students employed planning strategies. I begin with evidence of the students trying to make sense of the problem before launching into their solution to the problem. Statements that demonstrated this were: “Let’s think of what’s happening” (T2, Iron) and “Just write down everything first so that we can get an idea of what’s going on” (T2, Titanium).

The students were attentive to identifying the given information from the problem. Two examples demonstrate different levels of this skill. In the first case, Zinc comments, “I’m thinking it gave you the grams of the alkali metal sulphate to start with so you must have to do something with that” (T1, Zinc). This student thought that all information given in a problem must be of use and has not considered the relevance of the given information. In the example that follows from the second TAPPS protocol, Zinc considered the given information more critically:

Okay so we have 27.82 grams of hydrated sodium carbonate crystals and that was dissolved in water to make one litre of solution, 25 millilitres of the solution was neutralized by 48.8 millilitres of hydrochloric acid. I’m thinking there’s numbers in there that were not doing anything right, but I don’t know if they’re relevant (T2, Zinc).

All pairs were able to identify the goal of both problems. Commonly, the students restated what was asked in the problem. The language used to express this included,
“We’ve got to determine” (T1, Argon), “We need to find out” (T1, Zinc), and “We need to find” (T2, Iron). Two comments stood out as being more interpretive. Argon commented, “We can easily find the identity of the alkali metal from its molar mass” (T1, Argon). Argon made the connection that the molar mass was unique to the particular element. Iron expressed the goal of the problem in his own words showing that he had a clearer understanding of the problem. He said, “So we need to find out how much of that is Na₂CO₃ and how much is water” (T2, Iron).

A component of planning demonstrated by the students was their identification of previous strategies that were relevant to the current problem. At an elementary level, the pairs referred to their notes in search of examples of related problems. As an example, Argon commented “Give me one second, I’m just going to grab my book. Okay. See most of these equations were converted to moles” (T2, Argon). In the next two examples, the students went beyond seeking a recipe to follow for the problem. Iron compared a past problem to the current problem. “Because usually like in our other questions they gave us the number of moles of the hydrate, not the hydrate, the part before it, the water, the Na₂CO₃ in this case” (T2, Iron). Germanium took this a step further, identifying the way in which a past problem was different from the current problem:

Okay, so what we used to do was find the mass of H₂O. Okay, yeah right so what we forgot to do, we need to subtract the mass of H₂O. See they knew the moles. That’s the problem. We have the total mass, grams, but we don’t know what the Na₂CO₃ weighs on its own. (T2, Germanium)
The students varied in the way they made use of previously learned strategies. At the simplest level, the students had a tendency to execute familiar operations without thinking through how that calculation would link to other steps that would eventually satisfy the goal. Using previous knowledge in this way hindered the learners from moving forward in the question. The following action by Lithium is evidence of this low level planning: “Okay I’m just going to find the moles for this because that’s the only thing that we clearly know how to do right now” (T2, Lithium). Titanium provided another example of this short sighted planning when he suggested, “I think we should just try that C equal N over V thing just to get how many moles of hydrochloric acid we have and then we can go from there” (T2, Titanium). In both examples, the problem solver knew how to calculate moles, and attempted this as a single isolated step without thinking through the series of linked steps needed to solve this complex problem. The following two examples provide evidence of the students devising a plan that linked more than one step together. Iron assembled the following plan: “So if we find out how much of that .502 is sulphate, we can figure out how much of it is an alkali metal can’t we? And then from knowing that, we can determine which alkali metal it is” (T1, Iron). Germanium described a series of connections when he said, “we have the concentration so we can get the moles and then with the moles we can convert from moles of hydrochloric acid to moles of sodium carbonate hydrate” (T2, Germanium).
Monitoring

Three types of metacognitive monitoring emerged from my analysis of the TAPPS transcripts: screening, justification, and revision. All monitoring began as screening where the students checked an intermediate action. Higher levels of monitoring were demonstrated when students combined screening with justification and or revision. Students exemplified screening with statements like, “Wait, I’ll check if it’s [the chemical equation] balanced first” (T2, Titanium), “Oops, that doesn’t make sense” (T1, Zinc), and “let’s double check. No, this doesn’t work” (T2, Boron). Other types of monitoring were coupled to screening. I noted a number of instances where after screening, the students justified why an action did or did not make sense. In the following excerpt, Lithium recognized that the answer obtained for an intermediate calculation was reasonable because it was in the expected size range.

Iron: Is that the answer?  
Lithium: Well that would make sense because look, our numbers are low here and we need to subtract it from here. (T1, Iron and Lithium)

In the next two examples, the students were alerted to a flaw in their method because of the magnitude of the numbers involved. First, Lithium explained: “That doesn’t make sense. Our number of moles for sodium is more than our number of … moles for the hydrate, it’s a bigger number. So you can’t subtract it” (T2, Lithium). Secondly, an exchange between Germanium and Zinc, showed both members of the pair arriving at the same explanation for why their attempt was faulty.
Germanium: Yeah, I’m just thinking that’s going to be a lot of hydrate which doesn’t make a whole lot of sense.
Zinc: But you only have 0.2586 grams of your [sodium carbonate]. Oh yeah, I see what you mean because you’re using mass.
Germanium: Yeah, you know what I mean, because the total mass is 27.82. (T2, Zinc and Germanium)

The following exchange between Boron and Argon, demonstrated screening followed by revision. Boron suspected an error, Argon initiated retrying the balanced equation, and Boron corrected the mistake.

Boron: But that’s wrong I think.
Argon: Let’s try the balanced chemical equation thing again like just from scratch.
Boron: Oh! That’s what went wrong, ah, so it’s X₂S₀₄ for the first one. (T1, Boron and Argon)

In a number of cases, the students alluded to the need to revise their approach but did not immediately know how to redirect their efforts. One example of this occurred when Argon commented, “Okay well that’s really frustrating because I can’t find how much this is because I don’t know how many H₂O I have” (T2, Argon). Other instances of this were signaled by language like: “just one second I’ve got to think about this” (T1, Iron), and “I have to think it in my head” (T2, Lithium).

The final two examples show how the students coordinated screening, justification, and revision. First, after an unfruitful attempt to solve the problem methodically, Germanium suggested trying a value for the hydration number. This trial and error approach lacks thoughtful planning; however, Germanium exhibited monitoring by checking the remainder of the solution for consistency. Germanium began, “the
problem is the moles, like maybe the balanced equation. Mmm I’m thinking we should balance it assuming “x” is one at first.” Later, Germanium justified this action by noting, “Maybe that means there’s only one hydrate because that is the balanced equation.” Germanium continued to check the correctness of the value selected commenting, “everything else right now fits” (T2, Germanium). In the second example, Boron proposed an alternative approach to correct a wrong turn:

I don’t know if that’s going to work because .502 divided by 96.07 you just gets a ridiculously small number. We’re forgetting it’s x plus 96.07. Well we could try something with the .672 grams of BaSO₄. (T1, Boron)

Evaluation

The students’ comments about their answers to the problems revealed two levels of evaluation: intuition and reason. First, I present three examples of what I interpreted as intuition. Common to these examples was the students’ “feelings” that the answers were right or wrong. First, Iodine abandoned his systematic approach and guessed at a final answer at the end of the first TAPPS activity. He concluded the session with, “I think I’m going to go with sodium. I’ve got a good feeling” (T1, Iodine). In the following discussion, Lithium presents two hunches. Initially, Lithium mistakenly thought that hydrogen was an alkali metal and could be the answer. After further consideration Lithium suspected that a more rigorous approach to solving the problem is required.

Lithium: If it is dissolved in water, water has hydrogen and hydrogen is an alkali metal.
Iron: Yes but that doesn’t mean it has to be hydrogen does it?
Lithium: I don’t know it kind of just seems obvious to me. But I don’t think that’s the answer to the question because I feel like it’s a little more. (T1, Lithium and Iron)

In the last example, Germanium suspected that their solution was incomplete because it was based on an assumption. Germanium noted, “And then the “x” equals 1, that’s what we assume but we didn’t really, I don’t know, I think we missed something” (T2, Germanium).

The next three examples show the students using reasoning to evaluate their answer. In the first case, Germanium understood that the final answer for the problem could be checked by comparing it to the mass for each alkali metal. He directed Zinc to do this comparison: “Well does it add up to one of them?” (T1, Germanium). In the second example, Argon realized that their attempt to calculate the molar concentration of the hydrate did not match the goal of the problem. She commented, “Yeah but it’s asking for the molar mass of the hydrate. That’s not the molar mass” (T2, Argon). Finally, Lithium explained that their final answer was incorrect because the amount of the anhydrous compound was impossibly greater than the amount of the entire hydrate. She stated: “We thought we had it and then all of a sudden we realized that our number was too high” (T2, Lithium).

**The Metacognitive Framework as a Useful Model for Problem Solving**

My fourth research question was to determine if the Metacognitive Framework provided a useful model for problem solving. I used two analyses to address this question: (a) Chlora’s observations and reflections from the intervention period expressed
The Model for Problem Solving as a Scaffold for Students’ Problem Solving

A theme that emerged from my analysis of Chlora’s exit interview was that the Metacognitive Framework translated into a problem solving model that acted as a scaffold for students’ problem solving. Chlora replaced the word ‘framework’ with the word ‘model’ frequently during the interview. This reflects her interpretation of the Metacognitive Framework as a model for problem solving and her observations that her students applied it in this way. Chlora recalled that a part of her introduction of the Metacognitive Framework to the class involved calling on the students to identify what they had done as a class to solve a sample problem. She noted that the students “came up with pretty much all the significant or major points of the model.” Chlora suspected that some of the students were somewhat familiar with parts of the Metacognitive Framework from their past problem solving experiences. However, the Metacognitive Framework provided the students with an explicit way to approach problems. Chlora stated:

I think the kids probably know all the steps somehow but they don’t always put them together because I think there’s a feeling of panic when they read a question that’s not like one they’ve seen before, and when that happens all of the things that they know about their problem solving go out the window. Making it explicit brings it to the forefront in their thinking.

Chlora observed that the students’ response to the Metacognitive Framework was positive. The students “seemed pretty keen on having something or a plan on how they could approach questions.”
Chlora incorporated the Metacognitive Framework into written and lab problems across three units of study over a four month period. New types of problems were introduced to the students using a hand-out that included a metacognitive checklist adapted from the Metacognitive Framework under each example. In the following excerpt, Chlora described her presentation of new types of problems to the class. Noteworthy is that she reworded the checklist as metacognitive questions. “Every new question or every new idea that we came to, I used our model and said okay let’s think about that model. Let’s evaluate what we know. What are our goals? What relationships do we know? Are they relevant?” Chlora noted, “with repetition as we did through the semester, we were consistently reinforcing the way we could approach new and interesting questions.”

The identification of previous knowledge that is relevant to a current problem is at the front end of the Metacognitive Framework. Chlora presented the Mole Highway (see Appendix R) as a useful heuristic for her students to review at the start of new problems. The Mole Highway is “another fixed place to hang our hat and make connections. They can see that we’re really talking about all the same stuff, just looking at different conditions.”

The Metacognitive Framework included the checking and revising cycle that are key to the monitoring and evaluation part of the problem solving process. Chlora modeled these metacognitive skills while working on problems with the students on the board. A benefit to this cooperative approach was that the students “feel more part of
what we’re doing. And that I think has been a really positive outcome, that they feel that they’re contributing to our lesson.” On occasion, the students would proceed down a wrong pathway. Rather than immediately correcting the students, Chlora used this as an opportunity for her to reinforce the evaluation part of the framework. When the students realized that an answer seemed incorrect, Chlora would comment, “Well, why is it not?” In another example, Chlora recalled working with a student who found the course very difficult. She showed how this student made headway with the evaluation part of the framework. “The very fact he recognized that his answer didn’t make sense, caused him to go back to the beginning and rework.” Chlora also commented, “I think when the student had that struggle and realized it was wrong was really significant because he’s thinking about what he’s doing and thinking about his thinking.”

Chlora described how the students used the Metacognitive Framework during the semester to enhance their problem solving skills. Here is one description she provided.

One particular student I’m thinking of did it [the model] very consistently with all of the work that he did, and there was an improvement over the semester in how he approached the question, the amount of detail, and attention to the detail improved. He recognized that any information needs to be considered important until you sort of refine where you think you’re going with the question. Then he started deciding what he needed, and where he needed to go.

Chlora was impressed when one student who “really applied this model wholeheartedly to everything he did” was able to extend his use of the model to consolidate his conceptual understanding of the VSEPR theory.

He took the note that we gave and he made his own graphic organizer of how he connected the things together, and asked if that was an appropriate way to
organize his thinking about that concept. It wasn’t anything I had shown him or he had seen anywhere before. He was starting to take that next step in how to think about things, organize things, dissect things, and see relationships between things. I think that all speaks to the model.

Chlora remarked that the Metacognitive Framework supported students’ problem solving in different ways. It made the problem solving process “explicit to aid those students who are not intuitive in their problem solving,” Other learners had already internalized parts of the framework in their approach to problem solving.

I think[for] kids who are somehow using it on their own anyway, it’s only substantiating their thinking and the use of it, and even just increasing the awareness of it will help them when they come to a problem that they find challenging or they’re uncomfortable with.

During the Grade 11 chemistry course, the students were exposed to both pen and paper style problem solving tasks and experiment based problem solving tasks. The design labs in particular offered the students’ another setting in which to practice the Metacognitive Framework as a problem solving model. A design lab is “like a problem without numbers where they had to apply concepts we learned in class to solve a problem”. Chlora noted that the Metacognitive Framework supported the students in writing lab reports. “Another place where we could talk about how this model has helped is in their conclusions. The quality of the conclusions that I have read have dramatically improved over the semester in terms of how they evaluate their lab, and how they used the data to support the findings”. Chlora described one student’s experience with the final design lab (DL-4) in greater detail:
The egg lab drove him crazy because he just couldn’t quite get his head wrapped around how all these things came together, and he came in probably five or six times to just talk about what was going on in that lab. And when he handed in his Conclusion you can tell that there was a lot of thinking, just the progression in his ideas and how they connect together really complemented the model we’ve used. He started with the general and then he got more specific. He came up with an evaluation at the end that connected everything together.

Chlora reinforced the connection between the Metacognitive Framework and lab activities through her evaluation of the students’ lab reports. “The feedback on their labs directed them to apply the model to their investigative or inquiry work.”

Overall, Chlora suggested that the Metacognitive Framework supported the students’ problem solving process by giving them “greater confidence because they have something they can go back to every single time.” The Metacognitive Framework was “one thing kids will gravitate to and then applying new concepts doesn’t seem quite so frightening to them. They’re more confident in their work.”

**How Students Used the Metacognitive Framework**

At the end of the intervention, I surveyed the students to determine how useful they found the Metacognitive Framework as a model for problem solving. Twenty of the students responded. The students were asked to rank the usefulness of the Metacognitive Framework as a model for problem solving on a 1 to 5 visual analog scale with 5 being *very useful* and 1 being *not useful at all*. In addition, I asked them to support their opinion with comments. Sixty percent of the respondents found the model to be *useful* or *very useful*, 25% found it *somewhat useful*, and 15% found it had limited or no usefulness to them. Following are examples of students’ comments about the overall usefulness of the
framework. “I have learned how to efficiently solve new problems by using previous theory and careful planning” (SF, Germanium). “I have learned how to fully observe and analyze a question to make it less challenging than it really is” (SF, Carbon). The framework was “a way of tracking and sorting my thoughts into an organized amount of knowledge” (SF, Manganese).

I also asked the students to identify the part of the Metacognitive Framework they found most useful and least useful. More than half the students reported the parts associated with planning were most useful. I then examined the comments by achievement group, and looked for a trend in how each achievement group used the Metacognitive Framework. The lower achievement group reported that identifying what was learned previously that might be useful in the current problem was of most use to them. A comment that exemplified this was, “What I have learned gets me thinking” (SF, Magnesium). The trend for the higher achievement group was that planning was most useful. One student reported, “I learned how to analyze problems better and break them down so they are less stressful” (SF, Zinc). Others noted the following useful aspects of planning, “how to lay out a problem before hand” (SF, Titanium), and “finding the relations between the quantities” (SF, Neon). Students across all achievement groups reported that the identification of new knowledge gained from doing a problem was least useful to them. Examples of comments that show this were, “new knowledge seemed like a waste of time” (SF, Zinc), “what new things I have learned sometimes confuses me” (SF, magnesium), and “I didn’t analyze new things learned in the problem” (SF,
Vanadium). I found two additional comments insightful. One student noted that “being encouraged to speak out loud and discuss with partners” (SF, Lithium) was most useful. This comment speaks to the value of TAPPS activities as a support to students during problem solving activities. Another student commented “I follow this process without really thinking about it so all of it” is useful (SF, Calcium). This student may have internalized a problem solving process similar to the Metacognitive Framework prior to this study.

Chapter Summary

The students’ self-reportas of their use of metacognitive skills as measured by the MCAI were stable for both the pilot and study groups across the pre- and post-test measures. This suggests that the intervention did not change the students’ use of metacognitive skills. A comparison of the higher and lower achievement groups within the study group, suggests that the intervention may have a differential effect on the students’ use of metacognitive skills for the higher achievement group.

Both groups showed a significant improvement in their problem solving abilities as measured by the PSTs. Chlora spoke to the value of design labs as a setting in which students in the study group developed their problem solving skills and their scientific thinking skills. My analyses of these students’ lab reports for the pre- and post-test design labs provided further evidence that their problem solving developed over the semester. Specifically, the students became more consistent in their goal awareness throughout all
parts of the lab report, and their evaluation of the experimental design became more complex.

My analyses of the TAPPS protocols revealed that the students in the study group used metacognitive skills associated with planning, monitoring, and evaluation. The students’ demonstrated a range in the level of complexity within their planning, monitoring, and evaluation metacognitive skills. The students employed planning and monitoring skills equally, and they demonstrated evaluation skills to a lesser degree.

Finally, the students in the study group used the Metacognitive Framework as a model for problem solving. Chlora reported that the framework was a scaffold to students’ problem solving. The students’ comments suggest that aspects of the Metacognitive Framework helped them to solve chemistry problems.
CHAPTER 5
DISCUSSION

During this study, I explored students’ use of metacognitive skills during problem solving activities and the effects of explicit metacognitive instruction on their use of metacognitive skills and their problem solving abilities. My hypothesis was that instruction that targeted the development of students’ metacognitive skills would improve the students’ use of these skills and their abilities to solve chemistry problems. This hypothesis is well supported in the literature (Baird & Michell, 1987; Haidar & Naqabi, 2008; Hartman, 2001a; Henessey, 1999; Howard et al., 2001; Rickey & Stacy, 2000; Swanson, 1990; Yuruk et al, 2008; Zakaria, Yazi & Ahmad, 2009). My research was intended to contribute to the body of research about the relationship between metacognition and problem solving. Furthermore, my research may inform teaching practice and help teachers to better support students in their problem solving endeavors.

In the following sections, I discuss my research findings in response to my research questions. Next, I describe the limitations of this study and suggest ways to address these limitations. Following this, I describe the implications of this study to teaching practice. Lastly, I provide recommendations for future research.

The Effect of Metacognitive Instruction on Students’ Use of Metacognitive Skills

My experimental design enabled me to include both a pilot and study group in my study. Both groups were Grade 11 chemistry classes taught by the same teacher. The pilot group was taught in the semester prior to when the intervention was implemented with
the study group. For both groups, I administered the Metacognitive Activities Inventory (MCAI) to measure students’ use of metacognitive skills. To determine the effect of explicit metacognitive instruction on students’ use of metacognitive skills, the MCAI was given twice to students in both the pilot and study groups: once approximately six weeks into the semester (pre-test) and again ten weeks later (post-test). The study group was exposed to metacognitive instructional strategies during the 10-week intervention period. Students’ pre-and post-test MCAI scores were positively correlated for both the pilot ($r = 0.58$) and study ($r = 0.67$) groups. For both groups, a student’s pre-test metacognitive skill score tended to be related to his or her post-test score.

One way repeated measures analysis of variance (ANOVA) revealed that the pre- and post-test mean scores on the MCAI were not significantly different for either group. Also, the groups were not significantly different from each other on these measures. My hypothesis was that the students’ pre- to post-test scores on the MCAI would not change for the pilot group and would show a significant improvement for the study group. However, the results of my study suggest that the intervention did not change the students’ self-reported use of metacognitive skills. These findings are not in agreement with other studies that investigated the impact of metacognitive instruction on students’ use of metacognitive skills (Hartman, 2001a; Martinez, 1998; Schraw, 2001). I discuss the factors that may help explain these discrepant findings in the section titled, *Limitations of the Study*. 
I further explored a potential association between students’ overall level of achievement in the Grade 11 chemistry course and how the intervention affected their use of metacognitive skills. Within the study group, the MCAI mean scores for students in the higher achievement group were compared to the scores for students in the lower achievement group. One way repeated measures analysis of variance (ANOVA) showed that the mean scores were not significantly different within, and between the groups. Further analysis of these achievement subgroups showed a significant interaction between achievement group and MCAI scores. Students in the higher achievement group responded more to the intervention than students in the lower achievement group. Students in the higher achievement group showed more development of their metacognitive skills throughout this course. This outcome provides some evidence of an Aptitude Treatment Interaction (ATI). Cronbach and Snow (1977) explained ATI as the condition when a learner’s response to an instructional method (i.e. treatment) is determined by the learner’s abilities (i.e. aptitude). The students in the higher achievement group may be better equipped to incorporate new metacognitive skills into their repertoire of learning strategies. The presence of an interaction in my study suggests the need to differentiate metacognitive instruction to better meet the individual needs of the students in the class.
The Effect of Metacognitive Instruction on Students’ Abilities to Solve Chemistry Problems

I measured students’ problem solving abilities for both the pilot and study groups using a problem solving task (PST). To determine the affect of explicit metacognitive instruction on students’ problem solving abilities, one form of the PST (pre-test) was given to both groups six weeks into their Grade 11 courses. A different form of the PST (post-test) was given ten weeks later. Between the pre- and post-test events, Chlora implemented the intervention with the study group. No correlation was found between students’ pre- and post-test PST scores for the pilot group; however, for students in the study group, these scores were positively correlated ($r = 0.59$). Within the study group, a student’s pre-test PST score tended to be associated with his or her post-test score. The results of one-way repeated measures ANOVA revealed that the pre- and post-test mean scores on the PSTs were significantly different for both groups, and that the groups differed significantly from each other on these scores. The mean scores on the pre- and post-test PSTs were higher for students in the study group. No interaction was found between the group and the PST indicating that the groups showed a similar rate of improvement from the pre- to post-test PST. My hypothesis that the students in the pilot group would show less improvement was not supported as students’ problem solving abilities improved over the semester regardless of their exposure to metacognitive instruction.
I further explored a potential association between students’ overall level of achievement in the Grade 11 chemistry course, and the impact of the intervention on their problem solving abilities. Within the study group, the PST mean scores for the students in the higher achievement group were compared to the scores for the students in the lower achievement group. One way repeated measures analysis of variance (ANOVA) showed that the mean scores were significantly different within, and between the groups. Students in the higher achievement group scored significantly higher on the PSTs. No significant interaction between the achievement group and the mean PST scores was found. These results imply that students’ improvement in problem solving abilities was comparable for the students in the higher and lower achievement groups.

The statistical analyses produced no conclusive findings as to the effectiveness of the intervention. In contrast, my analyses of the exit interview with Chlora and students’ lab reports suggests that the metacognitive instructional strategies did have a positive effect on both students’ problem solving abilities and their scientific thinking skills. Chlora noted that students’ thinking about inquiry activities developed over the semester. My comparison of the students’ reports for the pre- and post-test labs revealed development in the students’ problem solving skills. In their reports for the post-test lab, the students consistently addressed the goal of the experiment in their procedural design, analysis of data, and formulation of a conclusion. In the evaluation of their experiments, the students progressed from identifying elementary flaws to critiquing their design. In their final lab report, the students specifically explained how errors in their experiment
influenced the results. Particularly impressive was that by the end of the intervention, the students were able to apply concepts learned in class to solving lab based problems. Students demonstrated this by describing alternate procedures and analyses to measure the composition of eggshells. These design labs provide a context for students’ problem solving that mimics the way scientists problem solve in their research. These labs appear to have helped students to forge a connection between theory and practice.

**Metacognitive Skills Used By Students While Problem Solving**

The TAPPS protocols provided evidence of how students used metacognitive skills while problem solving and revealed different levels of these skills. Analyses of the TAPPS protocols provided evidence for the metacognitive skills associated with planning, monitoring, and evaluation. The students used planning and monitoring skills equally. Planning skills included making sense of the problem, extracting the given information, identifying the goal, seeking strategies used in the past, and mapping a solution. Furthermore, different levels of sophistication of planning were apparent. Lower level planning was demonstrated when students restated the goal, applied familiar algorithms, or executed isolated numerical calculations without a clear sense of direction. In contrast, higher level planning was demonstrated when students interpreted the goal, compared the context for their use of strategies in the past to the context of the new problem, or described a series of linked steps before beginning numerical calculations. Students’ different levels of planning reflect the characteristics of novice and expert problem solvers described by Heyworth (1999). He proposed that expert problem solvers
differed from novice problem solvers in their qualitative representation of problems. Expert problem solvers were able to describe a method to solve the problem in advance of doing any calculations while novice problem solvers focused on using formulae to generate a numerical result.

The students demonstrated monitoring when they screened for errors, justified their judgments, and made revisions to correct wrong turns. Students who combined these metacognitive skills demonstrated a higher level of monitoring. In particular, students’ justifications of their judgments were essential for them to resolve their misconceptions and progress to the next stage of problem solving (i.e., revision). A part of this process included periods of reflection when the students took time out from executing actions to think about what revision actions they would pursue next. Students’ attention to thinking before acting was evidence that they valued metacognitive activities as part of their problem solving process.

The students demonstrated evaluation through their comments on the correctness of their final answer. The students showed two levels of evaluation: intuition and reason. Intuition was the students’ sense of the correctness of a solution. Reason was demonstrated when students elaborated on why a solution was correct or not. The students’ depth of understanding of the problem was shown by whether this judgment was based on intuition or reason. Students who were able to explain why an answer was incorrect demonstrated a deeper analysis of their solution to the problem. Research by
Kramarski and Zoldan (2008) supports the importance of students’ analysis of errors as a means to reduce conceptual errors.

It is apparent from my analyses that there is considerable overlap in the metacognitive activities associated with monitoring and evaluation. Both involve students checking their work. In the case of monitoring, students check intermediate actions, and during evaluation they check a final answer. Evaluation becomes more distinctive when it progresses beyond assessing whether a solution to the problem has been found.

Metacognitive evaluation includes students proposing alternate solutions and reflecting on what new things they learned by attempting the problem. My analyses of the TAPPS protocols provided no evidence of students engaging in these aspects of evaluation. An explanation for this may be that the students did not have enough time at the end of the TAPPS session to demonstrate further evaluation skills. Alternatively, the framework may require more explicit structures to deal with these aspects of evaluation.

The Metacognitive Framework as a Useful Model for Problem Solving

The introduction of the Metacognitive Framework was central to the metacognitive instructional practices implemented during the intervention. The value of the framework as a support to students’ problem solving was revealed during the exit interview with Chlora and from students’ responses to the survey of their use of the framework. During the exit interview, Chlora described the value of Metacognitive Framework as a problem solving model; it became a scaffold for students’ problem solving. The framework provided students with a starting point and an organized way to
advance through complex problems. The front end of the Metacognitive Framework reminded students to use previous knowledge including heuristics as a starting point in new problem solving scenarios. The value of a repertoire of heuristics is supported by Barak (2010). The ability to start the problem encouraged students to persevere in their attempt formulate a solution to the problem. Chlora’s modeling of the monitoring and revision cycle while doing example problems with the students showed the students that problem solving was not obstacle free and that putting forth the effort to use the framework could make their efforts more fruitful.

Chlora noted that students’ confidence increased as they practiced using the framework. As a model for problem solving, the Metacognitive Framework provided students with a general and methodical way to approach challenging problems that otherwise may have intimidated them. Students who adopted the Metacognitive Framework as a model for problem solving were more confident in their ability to solve problems. The literature suggests that students’ beliefs that they can solve a problem have a positive effect on their problem solving success. Taasoobshirazi and Glynn (2009) showed that chemistry students’ self-efficacy influenced their selection of appropriate problem solving strategies and resulted in students demonstrating greater persistence to solve difficult problems.

Lastly, Chlora remarked that the individual problem solving needs of the student determined how different learners made use of the Metacognitive Framework. For students who were not intuitive in their problem solving, the framework made the process
explicit. The importance of making the process explicit has been shown to make metacognitive instruction more effective (Hartman, 2001a; Gredler, 2009). For others who had already internalized a problem solving process, the framework substantiated their thinking. This interpretation aligns with research by Case and Gunstone (2002). They noted that learners who had already integrated metacognitive skills into their problem solving approach consolidated their use of these skills when they were exposed to further metacognitive instruction.

Students’ responses to the survey indicated that most found the Metacognitive Framework useful as a model for problem solving. Students in the higher achievement and lower achievement groups used the framework differently. Students in the higher achievement group identified planning aspects of the framework as most useful. Students in the lower achievement group identified retrieving previous knowledge as most useful. This pattern suggests that planning is a key to problem solving success. Both groups reported that the evaluation piece of the framework was least useful, which may indicate the need for teachers to more thoroughly address this part of the framework.

**Limitations of this Study**

The limitations of this study warrant further exploration. First, I discuss the factors that primarily limited the statistical results. Next, I present other weaknesses that limited the effectiveness of the intervention. Lastly, I propose an alternative research design that may subsequently address many of these limitations. A number of factors may explain why the hypothesized differences between the pilot and study groups were not
found. These factors include sample size, the absence of a control group, duration of the intervention, sampling method, measurement of metacognition, and the selection of problems for the pre and post-test PSTs. Certainly, the small sample size obtained for both groups is a weakness of this study. Consequently, the statistical analyses lacked power; the probability of finding group differences in students’ use of metacognitive skills and problem solving abilities was lowered.

Although I was able to field test the MCAI and PSTs with the pilot group, there was no control group for my study. The pilot group could not be isolated from instructional methods that could promote students’ acquisition of metacognitive skills. In particular, the pilot group participated in collaborative problem solving activities as part of the teacher’s normal classroom practices. These activities included students working with a partner to solve written problems and during experiments. The effect of this collaboration on students’ metacognitive skills and problem solving abilities is unknown.

The 10-week intervention may have been too short to influence a student’s use of metacognitive skills differentially. I designed the intervention for this study with the intent of transforming students’ approach to problem solving. This kind of outcome requires students to alter their thinking process, an outcome that is difficult to achieve over short time periods (Case & Gunstone, 2002). Other intervention studies focusing on students’ metacognitive development were conducted over a longer period of time. For example, both the Cognitive Acceleration through Science Education program (Adey &
Shayer, 1994) and Project Enhance Effective Learning (Baird & Mitchell, 1987) were implemented over two years.

As with many such school based intervention studies, these students were not randomly selected from the population. Students who opt to study Grade 11 chemistry have an interest in science and a comfort with standard numeracy skills. Even so, teachers comment that students in different sections (i.e., time slots) of the same course differ in their characteristics as learners. The scheduling of other courses influences the mix of students in each section. As a result, students with similar interests and abilities are more likely clustered into the same section, and there can be considerable differences between the sections. The potential differences between the students in the pilot and study groups could have confounded the results of my study.

It is difficult to obtain a true measure of the students’ use of metacognitive skills. Pintrich, Wolters, and Baxter (2000) identify construct validity as the main issue with measuring metacognition. In general, there is a lack of clarity in what is being measured. Coupled to this is a disconnect between what the theory predicts and what the data generate. Theory divides metacognition into a number of components such as planning, monitoring, and evaluation, while, factor analysis of self-report questionnaires (e.g., the MCAI) typically produce one factor (Cooper & Sandi-Urena, 2009). Hence self-report instruments may not capture students’ actual use of metacognitive skills. Additionally, since metacognition is an in-the-moment process, students may not remember their metacognitive experiences while responding to the questionnaire (Garner, 1987). Pintrich
et al. (2000) also report that data from self-report questionnaires are sensitive to construct-irrelevant variance that may come from students’ abilities to read the questionnaire and their attempt to provide desirable answers.

A number of limitations are specific to the MCAI. This questionnaire included eight negatively worded items that may have been confusing to some students in my study. Schmitt and Stuits (1985) noted that respondents often misinterpret negatively worded items. The MCAI was validated for university students (Cooper & Sandi-Urena, 2008); it may not be a valid instrument for high school students. The scale used in the MCAI measured the frequency of students’ use of metacognitive skills. My data revealed different levels of sophistication in the students’ use of metacognitive skills which were not captured by the MCAI.

The students’ problem solving abilities were measured using pre- and post-test problem solving tasks. Each test was a different task. Both consisted of an unfamiliar and challenging stoichiometry problem. The pre-test problem was more conceptual while the post-test was more computational. Since the tests were not equivalent, the observed differences in the students’ pre- and post-test scores may not be indicative of students’ improved problem solving abilities.

A number of factors limited the effectiveness of the intervention. The data from the TAPPS protocols were not as rich as I expected. The TAPPS procedure was introduced to the students during this study. The students were unaccustomed to verbalizing all their thoughts while problem solving. They were also unfamiliar with the
distinct roles of the problem solver and listener. Their roles were fluid with both members of the pair actively engaged in trying to solve the problem. The listener was not focused on encouraging the problem solver to articulate his or her thoughts. Sections of the transcripts contained fragmented verbalizations that were difficult to follow. The students required more practice with the format of the TAPPS protocol in advance of the audio recorded data collection events. The degree to which the students internalized their problem solving process also influenced the detail provided in their verbalizations (Garner, 1987; Pintrich et al., 2000). Metacognitive activities often occur at the subconscious level, and learners do not express them explicitly (Garner, 1987). Lastly, students experience increased cognitive load when asked to verbalize while solving a problem. Garner (1987) noted that this increased cognitive load could compromise a student’s ability to solve the problem. Ericsson and Simon (1980) add that students who are working on a problem beyond their cognitive ability either verbalize incompletely or shut down their verbalizations.

I adapted the Metacognitive Framework into metacognitive checklists for written and lab problems. The checklists were intended to remind students of useful metacognitive skills during their problem solving efforts. I did not word all parts of the checklist used for written problems as self-questions (see Appendix A). Self-questions that could have been included are: (a) What is the goal of the problem? (b) What are the relationships between the quantities? (c) How can I map out a solution? and (d) Does the solution answer the question? The value of self-questions to engage students in reflective
thought is well supported in the literature (Baird, 1986; Flavell, 1976; Hartman, 2001a; Kapa, 2007).

Two other limitations are noteworthy. I found no evidence of students’ attempts to answer the question: What new things have I learned while doing this problem? More explicit attention to this aspect of the Metacognitive Framework was needed during instructional time so that the students formally addressed it as part of their solutions to problems. Finally, the students’ written lab reports provided evidence of their problem solving abilities. However, they did not provide direct evidence of their metacognitive skills.

**Suggestions for Improvements: The Case Study Design**

Many of the limitations identified in the previous section could be addressed through design modifications. As an example, a case study design involving two to four students could be used to collect data using think aloud protocols, design labs, a problem solving journal, and an exit interview at the end of the intervention. This design would include analyses that follow each student through all the data. A potential outcome could be a richer, more coherent description of students’ use of metacognitive skills and problem solving process. Prior to the students’ exposure to explicit metacognitive instruction, they would begin their problem solving journal, participate in a think aloud protocol, and complete a design lab. Hence changes in the students’ behaviors before and after the intervention could be revealed.
As part of this new design, I propose a different way of conducting the think aloud protocols. The collaborative component of the TAPPS protocols has the potential to be valuable, but pairing the student problem solver with the teacher as an expert listener may provide richer information. The teacher’s expertise might better draw out each student’s problem solving process. Scaffolding provided by the teacher would also reduce the students’ repetition of faulty strategies. For example, Schoenfeld (1992) suggests that the teacher ask the problem solver guiding questions such as “What (exactly) are you doing?”, “Why are you doing it?”, and “How does it help you?” (p.356). Greater consistency in the role of the listener is attained when the teacher acts as the listener. Consequently, all problem solvers have a comparable experience during a think aloud protocol. Stronger evidence of students’ development of metacognitive and problem solving skills might emerge from such changes to the methods.

The use of design labs as a data source could be improved through video recording the students while they conduct experiments. Roychoudhury and Roth (1996) found this to be an effective method for observing how students interact with their lab partners during open inquiry activities. A video recording of students executing experimental work would better capture their use of metacognitive skills, especially their use of monitoring (Kipnis & Hofstein, 2008).

I would add two additional data collection methods: (a) a problem solving journal, and (b) an exit interview with the students. Throughout the intervention period, students would keep a problem solving journal in which they would include their
reflections about the problem solving tasks (i.e., pen and paper and lab problems).

Students would be asked to include their response to the question: What new things have I learned while doing this problem? Lastly, I would conduct an exit interview with each student. The purpose of the interview would be to gain further insight into how students used the Metacognitive Framework as a model for problem solving.

**Implications to Teacher Practice**

The results of this study provide a number of potential implications for teacher practice. Chlora shared how her experience with the intervention affected the way she approaches her practice. The following excerpt reveals how her participation in this study has stimulated her own reflections with respect to her teaching.

I’m always really interested in how kids learn, why they learn, and what drives them to learn. This really gives me a practical way to address those issues. I think this has helped me to do that, to really think about that. It’s just excellent professional development, being more conscious and aware of your teaching and how it impacts your students.

Chlora also spoke to the value of the Metacognitive Framework as a model for students to use while problem solving. The students’ comments about their use of the framework add credence to this claim. Chlora commented that, “the model needs lots of practice and needs to be practiced in other settings. It needs to be viewed as a broader way of organizing your thinking.” She suggested the framework be used in different settings such as essay writing or while doing math problems. Chlora concluded the interview with this remark, “I want to practice this model again and again because I really like it.” Chlora in collaboration with her teacher candidate opted to introduce the
Metacognitive Framework as a model for problem solving to her Grade 10 math students during the semester that followed this study. She was inspired to do so in an attempt to help her students improve their abilities to solve inquiry style math problems. Chlora implemented some revisions to the way she presented the framework to this class. She introduced it to the students with a problem without numbers. This helped students to build their qualitative representation of problems, a skill that characterizes expert problem solvers (Heyworth, 1999).

In addition, she explicitly addressed the last piece of the framework where students were asked to explain new things they learned by doing a particular problem. She observed that students’ achievement on inquiry problems rose from 57% ($SD = 22$) at the start of the course to 87% ($SD = 10$) at the end of the semester. This suggests that students benefitted from instructional time dedicated to developing their metacognitive skills. White and Gunstone (1989) note that students must first acknowledge that their current learning strategies are inadequate in order for them to pursue alternative strategies. Furthermore, students must see such alternatives as “plausible, intelligent and fruitful” (p. 585). These observations have implications to the way teachers present the Metacognitive Framework to their students. Initially, the framework could be introduced using straightforward problems so that the students could concentrate their efforts on learning to use the framework. With repeated practice, the students will learn how to make the framework more useful to them. Once students develop competence in using the framework, the students may gradually employ the framework with more complex
problems. Teachers could also put more emphasis on the planning component of the framework. In my study, students in the higher achievement group found that planning was supportive to their problem solving attempts. Students in the lower achievement group underutilized this aspect of the framework.

Chlora commented on the inclusion of design labs during the intervention. “I liked the way we approached the labs. If anything I’d like to do more like that right off the bat.” My research revealed that such activities may further help students to develop scientific thinking skills. Design labs offer students a hands-on setting in which to hone their problem solving skills. Students also see a purpose to developing problem solving skills when they are working on a problem they have largely devised for themselves.

**Future Research**

A number of areas for future research emerged from this study. The difficulty with measuring metacognition remains a challenge for researchers and practitioners. This partially stems from the lack of clarity in how metacognition is defined (Dinsmore et al., 2008; Pintrich et al., 2000). Measuring metacognition is further complicated by the disconnect between data and theory. Interesting questions arise from this. Should instruments that measure metacognition be more sensitive to the components of metacognition? Does categorizing metacognitive skills limit students’ development of these skills? What is a valid and reliable method for measuring students’ metacognition?

The difference between students in the lower and higher achievement groups in their development of metacognitive skills beckons further research on Aptitude
Treatment Interactions. How could metacognitive instruction be differentiated to better meet the needs of students with varying problem solving abilities?

While not part of my research, there is now the potential to link technology to the aspects of learning I focused on during my study. Computer environments can track students’ problem solving behaviours. Over my years of teaching high school students, I have noted that students become readily engaged in tasks that allow them to use computers. Two such platforms are Interactive MultiMedia Exercises (IMMEX) and metAHEAD. IMMEX tracks students’ use of strategies while they solve problems (Cooper, Sandi-Urena, & Stevens, 2008). MetAHEAD is an on-line tutorial that provides metacognitive support to students while they solve problems (Hollingworth & McLoughlin, 2001). Both allow researchers to collect and manage large amounts of data. Both allow students to direct their own problem solving approach. To date, neither program has been used with high school students. Future research could investigate how computerized environments could be used to build students’ problem solving abilities in high school chemistry.

Concluding Remarks

When I began this research, I set out to explore the link between chemistry students’ metacognitive skills and their problem solving abilities. I gained a rich understanding of the complex interplay between the teacher’s instructional strategies, students’ development of metacognitive skills, and students’ problem solving abilities. This was facilitated by the variety of data sources that contributed to the findings.
the intervention did not produce a measureable change in students’ metacognitive skills, there was qualitative evidence that metacognitive instruction enabled students’ problem solving. Students’ problem solving in the lab setting improved for students in the study group who applied the metacognitive skills introduced to them during the intervention. The value of design labs to develop students’ metacognitive skills, problem solving abilities, and their scientific thinking skills was apparent. An invaluable outcome of this research was that the Metacognitive Framework integrated metacognitive skills into an effective model for problem solving. The framework focused on skills that students could use during both pen and paper, and lab tasks. This flexibility reinforced the link between students’ learning in the classroom and in the lab setting. The insights gained into the different ways students use metacognitive skills provide direction for teachers to better address the individual problem solving needs of their students.
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## APPENDIX A:
### PEN AND PAPER PROBLEM SOLVING CHECKLIST

### ACTUAL PROBLEM

<table>
<thead>
<tr>
<th>Current Knowledge</th>
<th>Solving the Problem</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td><strong>Plan:</strong></td>
<td><strong>Evaluate:</strong></td>
</tr>
<tr>
<td></td>
<td>🗒️ Read the problem</td>
<td>❑ Check that the solution answers the question</td>
</tr>
<tr>
<td></td>
<td>🗒️ Determine the goal</td>
<td>❑ Check that the answer makes sense</td>
</tr>
<tr>
<td></td>
<td>🗒️ Sort the given information into relevant and irrelevant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>🗒️ Break the problem down into smaller tasks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>🗒️ Find the relationships between the quantities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>🗒️ Map out a solution</td>
<td></td>
</tr>
</tbody>
</table>

My Solution:

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# APPENDIX B:
LAB PROBLEM CHECKLIST

<table>
<thead>
<tr>
<th>Current Knowledge</th>
<th>Solving the Problem</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td>Plan:</td>
<td>Evaluate:</td>
</tr>
<tr>
<td></td>
<td>□ Identify the purpose. Be specific.</td>
<td>□ Check that the analyzed data adequately addresses the Purpose</td>
</tr>
<tr>
<td></td>
<td>□ What data is necessary to address the purpose?</td>
<td>□ Check that the findings make sense</td>
</tr>
<tr>
<td></td>
<td>□ Materials and equipment required</td>
<td>□ Describe limitations of the experimental process and ways to improve lab methods</td>
</tr>
<tr>
<td></td>
<td>□ Methods needed to collect the data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Do the instructions provide enough detail that relevant data can be collected?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can the experiment be repeated such that consistent results are produced?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>□ Create data tables to organize data.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>□ How will I analyze my data to address the purpose of the experiment?</td>
<td></td>
</tr>
</tbody>
</table>

My Design:
**APPENDIX C:**

**DETERMINATION OF THE FORMULA FOR A HYDRATE (DL-3)**

Given a sample of an unknown hydrate, how could you determine the formula for the hydrate?

<table>
<thead>
<tr>
<th>Current Knowledge</th>
<th>Solving the Problem</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td>Plan:</td>
<td>Evaluate:</td>
</tr>
<tr>
<td></td>
<td>❑ Identify the purpose. Be specific.</td>
<td>❑ Check that the analyzed data adequately addresses the purpose</td>
</tr>
<tr>
<td></td>
<td>❑ What data is necessary to address the purpose?</td>
<td>❑ Check that the findings make sense</td>
</tr>
<tr>
<td></td>
<td>❑ Materials and equipment required</td>
<td>❑ Describe limitations of the experimental process and ways to improve lab methods</td>
</tr>
<tr>
<td></td>
<td>❑ Methods needed to collect the data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Do the instructions provide enough detail that relevant data can be collected?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can the experiment be repeated such that consistent results are produced?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>❑ Create data tables to organize data.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>❑ How will I analyze my data to address the purpose of the experiment?</td>
<td>What new things have I learned while doing this problem?</td>
</tr>
</tbody>
</table>

My Design:
APPENDIX D:
MEASURING THE COMPOSITION OF EGGSHELLS (POST-TEST DESIGN LAB, DL-4)

Introduction: The component of eggshells that gives them strength and hardness is calcium carbonate, CaCO₃. Calcium carbonate reacts with hydrochloric acid by the following reaction:

\[
\text{CaCO}_3 (s) + \text{HCl} (aq) \rightarrow \text{CaCl}_2 (aq) + \text{CO}_2 (g) + \text{H}_2\text{O} (l)
\]

The portion of the eggshell that is not calcium carbonate does not react with the acid and remains a solid. 3 M HCl is an appropriate concentration of acid to completely react with the CaCO₃.

Design a lab to determine the % by mass of CaCO₃ in different types of egg shells.

<table>
<thead>
<tr>
<th>Current Knowledge</th>
<th>Solving the Problem</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td>Plan:</td>
<td>Evaluate:</td>
</tr>
<tr>
<td></td>
<td>Identify the purpose. Be specific.</td>
<td>☐ Check that the analyzed data adequately addresses the Purpose</td>
</tr>
<tr>
<td></td>
<td>What data is necessary to address the purpose?</td>
<td>☐ Check that the findings make sense</td>
</tr>
<tr>
<td></td>
<td>Materials and equipment required</td>
<td>☐ Describe limitations of the experimental process and ways to improve lab methods</td>
</tr>
<tr>
<td></td>
<td>Methods needed to collect the data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Do the instructions provide enough detail that relevant data can be collected?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can the experiment be repeated such that consistent results are produced?</td>
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</tr>
<tr>
<td></td>
<td>☐ Create data tables to organize data.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>☐ How will I analyze my data to address the purpose of the experiment?</td>
<td></td>
</tr>
</tbody>
</table>

My Design:
APPENDIX E:
METACOGNITIVE ACTIVITIES INVENTORY (MCAI)

Code Name: _________________________

Please read the following sentences. Circle a value from 1 (never) to 5 (Always) for each statement to describe the way you are when you are trying to solve a problem. Think back to the problem you just attempted. What do you do before you begin a solution? What do you do while you are working on the problem? What do you do after you have finish working on the problem? There are no right answers. Please describe yourself as you are, not how you think you should be. This will not be graded.

Survey Scale: 1 = Never …5 = Always

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I read the statement of a problem carefully to fully understand it and determine what the goal is.</td>
<td>12345</td>
<td></td>
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<tr>
<td>2</td>
<td>When I do assigned problems, I try to learn more about the concepts so that I can apply this knowledge to test problems.</td>
<td>12345</td>
<td></td>
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<tr>
<td>3</td>
<td>I sort the information in the statement and determine what is relevant.</td>
<td>12345</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
<td>Once a result is obtained, I check to see that it agrees with what I expected.</td>
<td>12345</td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td>I try to relate unfamiliar problems with previous situations or problems solved.</td>
<td>12345</td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>I try to determine the form in which the answer or product will be expressed.</td>
<td>12345</td>
<td></td>
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</tr>
<tr>
<td>7</td>
<td>If a problem involves several calculations, I make those calculations separately and check the intermediate results.</td>
<td>12345</td>
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<tr>
<td>8</td>
<td>I clearly identify the goal of a problem (the unknown variable to solve for or the concept to be defined) before attempting a solution.</td>
<td>12345</td>
<td></td>
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<tr>
<td>9</td>
<td>I consider what information needed might not be given in the statement of the problem.</td>
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<tr>
<td>10. I try to double-check everything: my understanding of the problem, calculations, units, etc.</td>
<td>1 2 3 4 5</td>
<td></td>
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<tr>
<td>11. I use graphic organizers (diagrams, flow-charts, etc) to better understand problems.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>12. I experience moments of insight or creativity while solving problems.</td>
<td>1 2 3 4 5</td>
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<td></td>
</tr>
<tr>
<td>13. I jot down things I know that might help me solve a problem, before attempting a solution.</td>
<td>1 2 3 4 5</td>
<td></td>
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</tr>
<tr>
<td>14. I find important relations amongst the quantities, factors or concepts involved before trying a solution.</td>
<td>1 2 3 4 5</td>
<td></td>
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<tr>
<td>15. I make sure that my solution actually answers the question.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>16. I plan how to solve a problem before I actually start solving it (even if it is a brief mental plan).</td>
<td>1 2 3 4 5</td>
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<td>17. I reflect upon things I know that are relevant to a problem.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>18. I analyze the steps of my plan and the appropriateness of each step.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>19. I attempt to break down the problem to find the starting point.</td>
<td>1 2 3 4 5</td>
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</tr>
<tr>
<td>20. I spend little time on problems for which I do not already have a set of solving rules or that I have not been taught before.</td>
<td>1 2 3 4 5</td>
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</tr>
<tr>
<td>21. When I solve problems, I omit thinking of concepts before attempting a solution.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>22. Once I know how to solve a type of problem, I put no more time in understanding the concepts involved.</td>
<td>1 2 3 4 5</td>
<td></td>
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<tr>
<td>23. I do not check that the answer makes sense.</td>
<td>1 2 3 4 5</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>24. If I do not know exactly how to solve a problem, I immediately try to guess the answer.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>25. I start solving problems without having to read all the details of the statement.</td>
<td>1 2 3 4 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26. I spend little time on problems I am not sure I can solve.</td>
<td>1 2 3 4 5</td>
<td></td>
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</tr>
<tr>
<td>27. When practising, if a problem takes several attempts and I cannot get it right, I get someone to do it for me and I try to memorize the procedure.</td>
<td>1 2 3 4 5</td>
<td></td>
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</tbody>
</table>
APPENDIX F:
PRE-TEST PROBLEM SOLVING TASK

Code Name: _________________________

Instructions: You will have 5 minutes to read and think about the question. After the reading time, you will have 10 minutes to consult with your partner about the problem. You will then have up to 40 minutes to work on the problem individually and to answer the Metacognition Questionnaire. For the Problem Solving Task, please show all of your work and record your answers on the Answer Sheet using a pen.

Worked Examples:
Look at the following reactions, shown by balanced equations:

i) \[ 2\text{NH}_3 \rightarrow N_2 + 3\text{H}_2 \]
(20 mL) (10 mL) (30 mL)

20 mL of ammonia breaks down to produce 10 mL of nitrogen and 30 mL of hydrogen.

ii) \[ \text{H}_2 + \text{Cl}_2 \rightarrow 2\text{HCl} \]
(10 mL) (10 mL) (20 mL)

10 mL of each hydrogen and iodine react to give 20 mL of hydrogen chloride gas.

Problems for you to try:

1. Write a general statement to describe the relationship between the volume of gases in a reaction and the balanced chemical equation.

2. What volume in mL’s of carbon dioxide will be produced in the following reaction?

\[ 2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \]
(30 mL) ( ? mL)

3. At about 450° C, phosphorus gas breaks up according to the following equation:

\[ \text{P}_4 \rightarrow ? \]
(20 mL) (40 mL)
What is the formula of phosphorus gas above 450° C?

4. a) Ozone is a gas. In a series of experiments, it can be shown that, for every 20 mL of ozone that break up, 30 mL of oxygen is formed. Surprisingly, no other element is involved. Write the balanced chemical equation for this reaction:

\[ \text{Ozone} \rightarrow \text{Oxygen} \]

(20 mL)  (30mL)

b) Two possible structures for ozone are:

A) \[ \text{O} \equiv \text{O} \equiv \text{O} \]  and B) \[ \text{O} \equiv \text{O}^+ \text{O}^- \]

Which structure do you think is most correct? Explain why you selected this structure.

c) Ozone in stratosphere protects us from harmful ultraviolet radiation from the sun. Chemicals in refrigerators and air conditioners called chlorofluorocarbons (CFC’s) break down this ozone by the following series of reactions:

\[ \text{CClF}_2 + \text{Cl} \rightarrow \text{ClO} + \text{O}_2 \]

With reference to the above sequence of reactions, why can a single iodine atom destroy thousands of ozone molecules?

d) Propose the formula for a compound that should have properties similar to a CFC but without the same damaging effects.
APPENDIX G:
POST-TEST PROBLEM SOLVING TASK

Code Name: _________________________

Instructions: You will have 5 minutes to read and think about the question. After the reading time, you will have 10 minutes to consult with your partner about the problem. You will then have up to 40 minutes to work on the problem individually and to answer the Metacognition Questionnaire. For the Problem Solving Task, please show all of your work and record your answers on the Answer Sheet using a pen.

Manure from livestock contains bacteria that convert some of the solids to methane (CH$_4$) gas. Methane is a much more potent greenhouse gas than carbon dioxide (CO$_2$). Methane can be burned as a source of energy. The complete combustion of methane converts the methane to carbon dioxide and water. A dairy farm near Kingston is investigating the possibility of collecting the manure from the fields and allowing it to form methane in large vessels. The methane would be collected and burned in a generator to make electricity that could be used to help run the farm. The farm has 50 head of cattle. The energy needed to run the farm is 50 000 kJ per hour. The following data are provided:

<table>
<thead>
<tr>
<th>Mass of a cow</th>
<th>455 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of manure produced by 1 cow in 1 day</td>
<td>2.3 kg</td>
</tr>
<tr>
<td>Mass of solids in manure that get converted to gas for 1 cow in 1 day</td>
<td>0.93 kg</td>
</tr>
<tr>
<td>Volume of methane produced per kg of fermented solids</td>
<td>560 L/kg</td>
</tr>
</tbody>
</table>

a) What volume of methane is produced from the manure produced by one cow in one day?

b) What volume of CO$_2$ gas is produced from the combustion of this amount of methane? (Assume that the reaction takes place at 25°C and 101.3 kPa.)

c) The energy available per mole of methane is 613 kJ/mol. Determine whether the manure process can provide the energy needed to run the farm.
APPENDIX H:
TEMPLATE FOR HOLISTIC RUBRIC

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
</table>
| 5     | Demonstrates complete understanding of the problem.  
       | The relevant variables are identified.  
       | The correct relationships between the variables have been found.  
       | A logical and organized solution has been presented.  
       | Numbers are reported with units.  
       | Mathematical operations have been correctly executed. |
| 4     | Demonstrates considerable understanding of the problem.  
       | The relevant variables are identified.  
       | The relationships found between the variables are mostly correct.  
       | A logical and organized solution has been presented.  
       | Most numbers are reported with units.  
       | The mathematical operations executed are mostly correct. |
| 3     | Demonstrates partial understanding of the problem.  
       | Some of the relevant variables are identified.  
       | Some of the relationships found between the variables are correct.  
       | The solution is presented with some logic and organization.  
       | Some numbers are reported with units.  
       | Some of the mathematical operations executed are correct. |
| 2     | Demonstrates little understanding of the problem.  
       | Few of the relevant variables are identified.  
       | Few of the relationships found between the variables are correct.  
       | The solution is presented lacks logic and is disorganized.  
       | Units are seldom reported with numbers.  
       | Few of the mathematical operations executed are correct. |
| 1     | Demonstrates no understanding of the problem.  
       | Few of the relevant variables are identified.  
       | Inappropriate relationships between the variables are used.  
       | The solution is presented lacks logic and is disorganized.  
       | Units are seldom reported with numbers.  
       | Mathematical operations are incorrectly executed. |
| 0     | No response/task not attempted. |
### APPENDIX I:
### THINK ALOUD PROBLEM SOLVING PROTOCOL 1

<table>
<thead>
<tr>
<th>Current Knowledge</th>
<th>Solving the Problem</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td>Plan:</td>
<td>Evaluate:</td>
</tr>
<tr>
<td></td>
<td>• Read the problem</td>
<td>• Make sure the solution answers the question</td>
</tr>
<tr>
<td></td>
<td>• Determine the goal</td>
<td>• Check that the answer makes sense</td>
</tr>
<tr>
<td></td>
<td>• Sort the given information into relevant and irrelevant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Break the problem down into smaller tasks</td>
<td>What new things have I learned while doing this problem?</td>
</tr>
<tr>
<td></td>
<td>• Find the relationship between the quantities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Map out a solution</td>
<td></td>
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</tbody>
</table>

My Solution:
### APPENDIX J:

**THINK ALOUD PAIR PROBLEM SOLVING PROTOCOL 2**

<table>
<thead>
<tr>
<th>Current Knowledge</th>
<th>Solving the Problem</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>What have I learned that might be relevant to this problem?</td>
<td>Plan:</td>
<td>Evaluate:</td>
</tr>
<tr>
<td></td>
<td>□ Read the problem</td>
<td>□ Make sure the solution answers the question</td>
</tr>
<tr>
<td></td>
<td>□ Determine the goal</td>
<td>□ Check that the answer makes sense</td>
</tr>
<tr>
<td></td>
<td>□ Sort the given information into relevant and irrelevant</td>
<td>What new things have I learned while doing this problem?</td>
</tr>
<tr>
<td></td>
<td>□ Break the problem down into smaller tasks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>□ Find the relationship between the quantities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>□ Map out a solution</td>
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</tbody>
</table>

**My Solution:**

27.82 g of hydrated sodium carbonate crystals, Na₂CO₃. xH₂O, was dissolved in water to make 1.00 L of solution. 25.00 mL of this solution was neutralized by 48.80 mL of hydrochloric acid (HCl) of concentration 0.100 mol/L. The products of the reaction are carbon dioxide (CO₂), water and sodium chloride (NaCl).

a) Write the balanced neutralization reaction.

b) Calculate the molar mass of the hydrate.
APPENDIX K:
THE GREAT OREO INVESTIGATION (PRE-TEST DESIGN LAB, DL-2)

Your Task

Design a lab to:

- investigate the ratio of icing to wafer for Oreo cookies in different brands of cream filled cookies
- investigate the claim: ‘Double Stuf”
- investigate the brand of cookie that offers the best value to the consumer

Guidelines:

1) Outline the independent, dependent and control variables.

2) Write a Materials and Procedure that will allow you to collect sufficient and relevant data.

3) Complete two trials.

4) Record all data in a properly formatted Data Collection table.

5) Analyze your data to address the three aspects of the Purpose.

6) Write a Conclusion and Evaluation that reports your calculated results. Identify two weaknesses in the experimental design and suggest ways to improve each.
APPENDIX L:
INTERVIEW GUIDE

1) Would you please describe your experience with each of the following instructional strategies?

a) Introducing the Framework to the students at the start of the intervention.

b) Your use of the Framework to model problem solving for the students

c) Providing students with the Framework each time a new type of problem was introduced
   - What was students’ reaction to the template?
   - How did students use the template during PS?
   - What aspect(s) of the template did students use?

d) Using the Framework to guide students during design labs

2) What evidence of students’ use of metacognitive skills did you observe over the course of the semester?

3) How did students’ PS behavior change during the semester?
   - How do these changes compare with your observations of other classes you have taught?

4) Would you like to add any other comments at this time?
APPENDIX M:
SURVEY OF THE STUDENTS’ USE OF THE METACOGNITIVE FRAMEWORK

You were introduced to the Metacognitive Framework during this semester. It appeared as a checklist on the handouts for problem solving tasks and Design Labs. I would like you to tell me how useful you found this as you worked through problems. There are no right answers. Please describe yourself as you are, not how you think you should be. This will not be graded. Please respond to the following.

1. Please rate the usefulness of the Metacognitive Framework as a model for problem solving on a scale of 1 (not useful at all) to 5 (very useful). ____________

2. Please share any overall comments you have about the usefulness of the Metacognitive Framework.

3. Please identify the parts of the Framework you found most useful.

4. Please identify the parts of the Framework you found least useful.
APPENDIX N:

LETTER OF INFORMATION TO THE PARENT/GUARDIAN

(IMPLICIT CONSENT)

Dear Parent/Guardian:

Your son/daughter is one of a group of Grade 11 students selected as potential participants for a research study, conducted as part of my Masters in Education thesis at the Faculty of Education, Queen’s University. The study is titled Learners’ Use of Metacognitive Skills While Problem Solving in High School Chemistry. The research has the support of the classroom teacher and the school Principal. This research has been cleared by the school board. This study was granted clearance by the General Research Ethics Board for compliance with the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans, and Queen’s policies.

As part of our ongoing attempt to help students be more successful in Grade 11 Chemistry, one of our goals is to help students to develop their thinking skills (i.e., metacognition). To this end, the teacher will be implementing a set of teaching strategies that focus on helping students to develop these skills in order to support their problem solving efforts in Chemistry. As part of the study, we will be monitoring the processes students use to approach Chemistry problems. Students participating in the study will complete two 20-minute questionnaires focused on metacognition. Non-participating students will use this time to work on a reading assignment. Participating students may also have two of their in class activities audio recorded.

The students will not be exposed to any more risk than normal classroom activities. None of the data used for my research will be shared with the classroom teacher. Participation is voluntary. Students are free to choose to participate or not participate in the research, knowing that their decision will not have any impact on their standing in their Chemistry 11 course. Following the procedures for data storage, the data from my research will be kept in a password protected computer, and the audio recordings will be destroyed once the data has been transcribed. Research findings will form the basis of my graduate thesis and may be published in professional journals or reported at conferences. In all publications and presentations of the findings, the names of individuals, the school and school board will be replaced by pseudonyms.

At no time will the actual identity of the participants be disclosed. Students’ confidentiality will be protected to the fullest extent possible and their names will not be used in any reporting of the results of my research.

If you do not wish your child to participate in this research please contact me at your convenience. You may also contact me if you have any questions or concerns. I may be reached by telephone at (613) 545-1902 x 3079, or by email at delvecch@alcdsb.on.ca. For questions, concerns or complaints about the research ethics of this study, contact the Education Research Ethics Board at ereb@queensu.ca or the Chair of Queen’s University General Research Ethics Board, Dr. Joan Stevenson, (613) 533-6081 (email: chair.greb@queensu.ca). If I have not heard from you by February 12, 2010, I will assume that you will allow your child to participate in this observational research.

Yours sincerely,

Francine Delvecchio
APPENDIX O:
LETTER OF INFORMATION TO THE STUDENT PARTICIPANTS

Dear Student:

You are one of a group of Grade 11 students selected as potential participants for a research study, conducted as part of my Masters in Education thesis at the Faculty of Education, Queen’s University. The study is titled Learners’ Use of Metacognitive Skills While Problem Solving in High School Chemistry. The research has the support of the classroom teacher and the school Principal. This research has been cleared by the school board. This study was granted clearance by the General Research Ethics Board for compliance with the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans, and Queen’s policies.

As part of our ongoing attempt to help students be more successful in Grade 11 Chemistry, one of our goals is to help students to develop their thinking skills (i.e., metacognition). To this end, the teacher will be implementing a set of teaching strategies that focus on helping students to develop these skills in order to support their problem solving efforts in Chemistry. As part of the study, we will be monitoring the processes students use to approach Chemistry problems. Students participating in the study will complete two 20-minute questionnaires focused on metacognition. Non-participating students will use this time to work on a reading assignment. Participating students may also have two of their in class activities audio recorded.

The participants will not be exposed to any more risk than normal classroom activities. None of the data used for my research will be shared with the classroom teacher. Participation is voluntary. The participants are free to choose to participate or not participate in the research, knowing that their decision will not have any impact on their standing in the Grade 11 Chemistry course. Following the procedures for data storage, the data from my research will be kept in a password protected computer, and the audio recordings will be destroyed once the data have been transcribed. Research findings will form the basis of my graduate thesis and may be published in professional journals or reported at conferences. In all publications and presentations of the findings, the names of individuals, the school and school board will be replaced by pseudonyms. At no time will the actual identity of the participants be disclosed. Your confidentiality will be protected to the fullest extent possible and your name will not be used in any reporting of the results of my research.

You may contact me if you have any questions or concerns. I may be reached by telephone at (613) 545-1902 x 3079, or by email at delvecch@alcdsb.on.ca. For questions, concerns or complaints about the research ethics of this study, contact the Education Research Ethics Board at ered@queensu.ca or the Chair of Queen’s University General Research Ethics Board, Dr. Joan Stevenson, (613) 533-6081 (email: chair.greb@queensu.ca).

Yours sincerely,

Francine Delvecchio
APPENDIX P:

LETTER OF INFORMATION TO THE TEACHER PARTICIPANT

Dear Teacher:

As a Master’s student at the Faculty of Education, Queen’s University, I am inviting you to participate in a formal research project. The study is titled Learners’ Use of Metacognitive Skills While Problem Solving in High School Chemistry. The research has the support of the school Principal. This research has been cleared by the school board. This study was granted clearance by the General Research Ethics Board for compliance with the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans, and Queen’s policies.

As part of our ongoing attempt to help students be more successful in Grade 11 Chemistry, one of our goals is to help students to develop their thinking skills (i.e., metacognition). To this end, I am asking you to implement a set of teaching strategies that focus on helping students to develop these skills in order to support their problem solving efforts in Chemistry. As part of the study, we will be monitoring the processes students use to approach Chemistry problems. I will visit the class four times during the semester to collect data. On two occasions, the students participating in the study will complete two 20-minute questionnaires focused on metacognition within the context of working on a problem solving task. Non-participating students will use this time to work on a reading assignment.

On two other occasions, the participants will take part in a paired think-aloud problem solving session. Each think-aloud session will take about 20 minutes. Four pairs of participants will be randomly selected to have their paired think-aloud session audio-recorded. On days of your choice, I will visit the class to observe your implementation of the instructional strategies. At the end of the study, I will invite you to participate in an interview. The interview will provide you with the opportunity to describe your experience with implementing the intervention, and your observations of how the participants responded to the instructional strategies.

The participants will not be exposed to any more risk than normal classroom activities. None of the data associated with the student participants will be shared with you. Participation is voluntary. Students are free to choose to participate or not participate in the research, knowing that their decision will not have any impact on their standing in their Chemistry 11 course. Your participation or non-participation in this study will have no effect on your employment standing. Following the procedures for data storage, the data from my research will be kept in a password protected computer, and the audio recordings will be destroyed once the data has been transcribed. Research findings will form the basis of my graduate thesis and may be published in professional journals or reported at conferences. In all publications and presentations of the findings, the names of individuals, the school and school board will be replaced by pseudonyms. At no time will the actual identity of the participants be disclosed. Your confidentiality will be protected to the fullest extent possible and your name will not be used in any reporting of the results of my research.

You may contact me if you have any questions or concerns. I may be reached by telephone at (613) 545-1902 x 3079, or by email at delvecch@alcdsb.on.ca. For questions, concerns or complaints about the research ethics of this study, contact the Education Research Ethics Board at ereb@queensu.ca or the Chair of Queen’s University General Research Ethics Board, Dr. Joan Stevenson, (613) 533-6081 (email: chair.greb@queensu.ca).

Yours sincerely,

Francine Delvecchio
APPENDIX Q:
GUIDELINES FOR A PAIR PROBLEM SOLVING THINK ALOUD PROTOCOL

In this activity you will work with a partner to solve a problem. This is a role-playing exercise. One of you will be cast as the Problem Solver and the other will the Listener. It is very important that you work together throughout this exercise. Please do not work independently.

The Problem Solver’s Task

1) Make a conscious effort to say EVERYTHING you are thinking. Attempt to explain your rationale for your approach to solving the problem to your partner.

2) Verbalize all thinking before you begin the problem – What, why and how are you going to approach the problem?

3) Verbalize all of your thoughts as you solve the problem. Consciously explain each step to the listener.

The Listener’s Task

1) Encourage the Problem Solver to keep verbalizing his or her thoughts throughout the entire process.

2) Think along with the problem solver. Make sure you understand each stage. If not, ask for clarification or greater detail.

3) Don’t let the problem solver get a head of you. Request him or her to slow down if necessary.

4) Check the problem solver at each step. If you suspect an error, don’t correct it. Point it out and have the problem solver attempt to fix it.
APPENDIX R:
THE MOLE HIGHWAY

THE MOLE HIGHWAY

MOLAR CONCENTRATION

SOLUTIONS

PARTICLES
Atoms of an element
Molecules of a compound

MOLE

X $6.02 \times 10^{23}$

/ $6.02 \times 10^{23}$

1 mol = 22.4L

GASES

PV = nRT
R = 8.314 kpa.Lmol⁻¹K⁻¹

VOLUME

PRESSURE
VOLUME
TEMPERATURE

X MOLAR MASS

X MOLAR MASS

MASS (grams)

/ MOLAR MASS