Western Michigan University
ScholarWorks at WMU

Dissertations | Graduate College

8-2007

An Investigation of Successful and Unsuccessful Students' Problem Solving in Stoichiometry

Ozcan Gulacar
Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/dissertations

Part of the Educational Methods Commons, and the Science and Mathematics Education Commons

Recommended Citation

Gulacar, Ozcan, "An Investigation of Successful and Unsuccessful Students' Problem Solving in Stoichiometry" (2007). *Dissertations*. 870.
https://scholarworks.wmich.edu/dissertations/870

This Dissertation-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Dissertations by an authorized administrator of ScholarWorks at WMU. For more information, please contact wmu-scholarworks@wmich.edu.

AN INVESTIGATION OF SUCCESSFUL AND UNSUCCESSFUL STUDENTS' PROBLEM SOLVING IN STOICHIOMETRY

by

Ozcan Gulacar

A Dissertation
Submitted to the
Faculty of the Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Mallinson Institute for Science Education

Western Michigan University
Kalamazoo, Michigan
August 2007

AN INVESTIGATION OF SUCCESSFUL AND UNSUCCESSFUL STUDENTS' PROBLEM SOLVING IN STOICHIOMETRY

Ozcan Gulacar, Ph.D.

Western Michigan University, 2007

In this study, I investigated how successful and unsuccessful students solve stoichiometry problems. I focus on three research questions:

1. To what extent do the difficulties in solving stoichiometry problems stem from poor understanding of pieces (domain-specific knowledge) versus students' inability to link those pieces together (conceptual knowledge)?
2. What are the differences between successful and unsuccessful students in knowledge, ability, and practice?
3. Is there a connection between students'

- cognitive development levels,
- formal (proportional) reasoning abilities,
- working memory capacities,
- conceptual understanding of particle nature of matter,
- understanding of the mole concept,

and their problem-solving achievement in stoichiometry?

In this study, nine successful students and eight unsuccessful students participated. Both successful and unsuccessful students were selected among the students taking a general chemistry course at a mid-western university. The students taking this class were all science, non-chemistry majors.

Characteristics of successful and unsuccessful students were determined through tests, audio and videotapes analyses, and subjects' written works. The Berlin Particle Concept Inventory, the Mole Concept Achievement Test, the Test of Logical Thinking, the Digits Backward Test, and the Longeot Test were used to measure students' conceptual understanding of particle nature of matter and mole concept, formal (proportional) reasoning ability, working memory capacity, and cognitive development, respectively. Think-aloud problem-solving protocols were also used to better explore the differences between successful and unsuccessful students' knowledge structures and behaviors during problem solving.

Although successful students did not show significantly better performance on doing pieces (domain-specific knowledge) and solving exercises than unsuccessful counterparts did, they appeared to be more successful in linking the pieces (conceptual knowledge) and solving complex problems than the unsuccessful student did. Successful students also appeared to be different in how they approach problems, what strategies they use, and in making fewer algorithmic mistakes when compared to unsuccessful students. Successful students, however, did not seem to be statistically significantly different from the unsuccessful students in terms of quantitatively tested cognitive abilities except formal (proportional) reasoning ability and in the understanding of mole concept.

UMI Number: 3287683

UMI®

UMI Microform 3287683

Copyright 2008 by ProQuest Information and Learning Company.
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

© 2007 Ozcan Gulacar

ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my major professors, Dr. Herb Fynewever and Dr. William Cobern, for their guidance during my studies in the U.S. and throughout my dissertation. I also thank the other members of my committee, Dr. Charles Henderson and Dr. Don Schreiber for their input and support. Debra Stoyanoff and William Merrow also have my appreciation for administrative support and technical support, respectively.

I also give great thanks to my wife, Ozlem, who has been especially tolerant of all my academic efforts. Her sacrifice enabled me to finish this. Her patience, helpfulness, and confidence in me have been precious throughout my studies. Nothing can describe how much I appreciate her unfailing support. I also thank my son, Eren, for his patience and understanding when I needed to study rather than spending time with him.

Many individuals wished me well, and provided positive support through this endeavor. They include Dr. Joseph Stoltman, Dr. David Rudge, Dr. Robert Poel, Dr. Marrisa Rollnick, and Dr. David Schuster. I am very grateful for all their support and encouragement.

Acknowledgements - Continued

I am fortunate to have many supportive mentors in the academic community. Dr. Aletta Zeitsman is one of those individuals who encouraged each step of this endeavor. I am extremely grateful for her support.

Other individuals whom I count as encouraging friends include Feridun Tasdan, Mustafa Sanver, Fatih Hasoglu, Adriana Undreiu, Pat Meyer, and Robert Ruhf. They each gave me many encouraging words.

I am very appreciative of the loving support of my family. My father, mother and siblings encouraged me throughout every step of the process.

Finally, to all of my friends, classmates, colleagues and students at Western Michigan University and Purdue University North Central who have provided enormous support throughout this process. I say, "Thank you!"

Ozcan Gulacar

TABLE OF CONTENTS

ACKNOWLEDGMENTS..... ii

LIST OF TABLES.....x

LIST OF FIGURES.....xii

CHAPTER

I. INTRODUCTION.....1

Statement of the Problem..... ...3

Importance to the Field.....6

II. LITERATURE REVIEW.....10

Chemistry and its Complexity.....11

Chemistry at Macro, Micro, and Symbolic Levels.....12

The Significant Characteristic of Chemistry: Particulate Nature of Matter (PNM)..... 14

Interrelation between PNM and Other Chemical Concepts.....15

Difficulties with Teaching, Learning and Using Particulate Theory.....17

Defining Problem and Problem Solving.....22

Towards a Unified Definition of "Problem" and "Problem Solving".....23

Examples and Non-Examples of True Problem: Problems versus Exercises.....26

The Influences of Distinction between Problem and Exercise.....29

Identifying Problem Solvers..... 31

Defining or Distinguishing Expert and Novice Problem Solvers.....31

Characteristics of Expert and Novice Problem Solvers.....32

Mysterious Journey to Becoming an Expert.....34

Table of Contents – Continued

CHAPTER

Characteristics of Successful and Unsuccessful Problem Solvers……36

Understanding the Sources of the Differences between Experts and Novices……37

Role of Knowledge Structure……38

Retrieval of Knowledge…… 47

Factors Affecting Problem Solving……50

Teaching vs. Teaching and Learning: Focusing on Students' Knowledge……50

Knowledge of Students……52

Conceptual Understanding and Problem Solving……58

Cognitive Development and Influence of Knowledge on Learning……64

The Effects of Proportional Reasoning on Problem Solving……67

Working Memory Capacity ……70

The Interaction of Problem Solving with More Factors……73

Domain Specific Knowledge……73

Strategies……75

Heuristics and Algorithms……77

Conclusion……78

III. METHODOLOGY……80

Research Questions……81

The Framework of the Selected Topic: Stoichiometry……82

The Structure of Stoichiometry Questions Used in the Study……84

Subjects……87

Overall Design and Data Collection Methods……92

Quantitative Test Descriptions……95

Table of Contents – Continued

CHAPTER

Qualitative Think-Aloud Protocol Description.....101

IV. RESULTS..... 105

Introduction.....105

Defining the Pieces.....106

Writing Chemical Equations (WEQ)..... 107

Balancing Chemical Equations (BEQ)..... 108

Mass Percent (MP).....108

Percent Yield (PY).....110

Empirical Formula (EF).....112

Molecular Formula (MF).....113

Limiting Reagent (LR).....114

Mole Concept (MC).....115

Stoichiometric Ratio (SR).....117

Extra Piece-Mathematical Ratio (MR).....118

The Codes for the Analysis of the Knowledge Pieces.....120

Successful (S)..... 120

Unsuccessful Did Incorrectly (UDI)..... 120

Unsuccessful-Guessed (UG).....121

Not Required (NR).....122

Could not Do (CD).....123

Did not Know to Do (DD).....126

Did Something Else (DSE).....127

Unsuccessful Received Hint (URH).....129

Table of Contents – Continued

CHAPTER

Reliability of Codes…….…….. 130

Answering the First Research Question……..131

Investigating the Pieces Involved in the Stoichiometry Problems ……132

Investigating the Total Success Rates in the Questions:
Linking or Pieces or Something Else?.....209

Answering the Second Research Question……..... 231

Performance on Individual Pieces By…….. 232

Non-Chemistry and Chemistry Objective Errors……..……251

Performance on Cognitive Tests……255

More Differences: Problem Solving Habits……..259

Answering the Third Research Question……260

Descriptive Statistics for the Longeot Test and Digit Backward Test……..262

Descriptive Statistics for the Mole Concept Achievement Test and
Berlin Particle Concept Inventory……..263

Correlation between the Total Success Rates and Cognitive Variables……265

Correlation between the Cognitive Variables and the Pieces……..267

Conclusion……271

V. DISCUSSIONS AND CONCLUSIONS……273

Comparison with Previous Research……273

Pieces and Linking……..275

The Nature of Students' Knowledge Achievement with Pieces…….. 276

Students' Success with Linking: Are Our Students Conceptual or
Algorithmic Problem Solvers?.....278

Differences between the Successful and Unsuccessful Students in the View
of Prior Research Findings on Experts and Novices……286

Table of Contents – Continued

CHAPTER

Knowledge Differences.....287

Strategy Differences.....289

Cognitive Ability Differences.....290

Significance of Several Cognitive Variables: Do they Correlate with Success?.....291

Understanding of the Mole Concepts (Mole Concept Achievement Test-MCAT).....293

Formal (Proportional) Reasoning Ability (Test of Logical Thinking-TOLT).....294

Understanding of the Particulate Nature of Matter (Berlin Particle Concept Inventory-BPCI).....295

Working Memory Capacity (Digit Backwards Test-DBT).....296

Cognitive Development (Longeot Test-LT).....298

Implications for Classroom Instruction.....301

Considering the Findings of the First Research Question.....302

Considering the Findings of the Second Research Question.....305

Considering the Findings of the Third Research Question.....310

Conclusion.....312

Contributions to the Field.....313

Limitations to the Study.....314

Recommendations for Future Research.....316

APPENDICES.....319

A. Human Subjects Institutional Review Board Approval.....319

B. The Chemistry Achievement Test.....338

C. The Test of Logical Thinking 339

D. Berlin Particle Concept Inventory.....340

Table of Contents – Continued

APPENDICES

E. Mole Concept Achievement Test……341

F. Longeot Test for Cognitive Development……342

G. Digit Backward Test for Working Memory Capacity……343

H. Stoichiometry Questions for Think-Aloud Protocols……345

I. Further Differences between Successful and Unsuccessful Students
(To be Operationalized in a Future Study)…… 353

BIBLIOGRAPHY……369

LIST OF TABLES

3.1: Simple Questions (Exercises) Used During the Think-Aloud Protocols.....84

3.2: Complex Questions (Problems) Used During the Think-Aloud Protocols.....85

3.3: All the Subjects in the Study 91

3.4: Types of the Questions in the TOLT.....96

4.1: Subjects' Performance with the Writing Chemical Equation Piece.....134

4.2: The Types of the Hints Provided for the Exercise #2.....135

4.3: Subjects' Performance with the Balancing Chemical Equation Piece 146

4.4: Subjects' Performance with the Mass Percent Piece..... 152

4.5: Subjects' Performance with the Empirical Formula Piece..... 160

4.6: Subjects' Performance with the Molecular Formula Piece.....168

4.7: Subjects' Performance with the Percent Yield Piece 173

4.8: Subjects' Performance with the Limiting Reagent Piece..... 180

4.9: Subjects' Performance with the Mole Concept Piece.....189

4.10: Subjects' Performance with the Stoichiometric Ratio Piece 197

4.11: Subjects' Performance with the Mathematics Ratio Piece 207

4.12: Students' Attempt Success Rates with all the Pieces.....208

4.13: The Total Success Rates of the Students from the Problems.....211

4.14: The Ranking of the Questions Based on the Average Number of the Pieces.....214

4.15: The TSRs and the ASRs of the Pieces Involved in the Problems.....216

4.16: Contextual Factors in the Questions.....224

4.17a: The Contextual Factors, Schemas, and the TSRs for Problems.....225

4.17b: The Contextual Factors, Schemas, and the TSRs for Problems 226

List of Tables - Continued

4.18: The Contextual Factors, Schemas, and the TSRs for Exercises.....228

4.19: The Comparison of the Attempt Success Rates (ASR) of the Successful Subjects to those of Unsuccessful Ones with Each Piece.....234

4.20: The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Exercises.....238

4.21: The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Problems.....240

4.22: The Comparison of the Codes Assigned to the Pieces Done by the Unsuccessful and Successful Students in the Exercises.....244

4.23: The Comparison of the Codes Assigned to the Pieces Done by the Unsuccessful and Successful Students in the Problems.....246

4.24: The Comparison of the Errors with Algorithm and the Calculators 252

4.25: The Comparison of the Unit Errors.....253

4.26: Results of the Tests for Cognitive Variables Affecting the Problem Solving Success.....258

4.27: Descriptive Statistics for the Cognitive Ability Tests.....261

4.28: The Nonparametric Correlations among the Several Cognitive Variables Affecting the Subjects' Problem Solving Performances.....264

4.29: The Correlation Coefficients for the Cognitive Variables and the Pieces.....270

LIST OF FIGURES

2.1: Experts' Knowledge Store.....40

2.2: Novices' Knowledge Store.....41

2.3: Unorganized Knowledge of Novices.....44

2.4: Hierarchical Knowledge of Experts.....44

2.5: A Common Pattern Used for Stoichiometric Calculations 69

3.1: The Main Pieces Used in Stoichiometry Problems and the Roadmap Used in Solving Stoichiometry Problems.....83

4.1: Total Success Rates as a Function of the Average Number of Pieces in both Problems and Exercises.....215

4.2: Total Success Rates as a Function of the Number of Piece Types in both Problems and Exercises.....215

4.3: Schema for Solving the Problem 7.....218

4.4: Schema for Solving Problem 10.....219

4.5: Schema for Solving Problem 9.....219

4.6: Schema for Solving Problem 3.....220

4.7: The Comparison of the Attempt Success Rates of the Successful Subjects to those of Unsuccessful Ones with Each Piece.....235

4.8: The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Exercises.....239

4.9: The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Problems.....241

4.10: Percents of the Codes Assigned to the Pieces Done By Successful and Unsuccessful Students in the Exercises.....245

4.11: Percents of the Codes Assigned to the Pieces Done By Successful and Unsuccessful Students in the Problems.....247

4.12: Comparison of the Test Results for Cognitive Variables Affecting the Problem Solving Performance.....257

CHAPTER I

INTRODUCTION

Problem solving is a very important task to all people. People survive because they are successful at solving all sorts of problems that they encounter in their everyday lives. Some of the problems people solve include quite difficult ones such as choosing a profession, moving to a new town, buying a house, getting used to a new job, and supplying everything that a family needs. Although people tackle remarkably different types of problems, despite occasional mistakes, human beings overall are good problem solvers and survivors in their daily lives.

On the other hand, in the academic realm, students have difficulty solving problems. Not only from a specific school, city or country but also from many other countries we hear that teachers complain that their students are poor problem solvers. Researchers have been trying to find the reasons behind the students' poor problem solving performances. There are still so many questions, however, waiting to be answered about the mysterious problem solving process.

Specifically, we want to know why students are not good at solving our kind of problems: scientific problems (e.g. Johnstone, 2001).

A student who can solve challenging everyday problems successfully may fail while dealing with a scientific problem although the basic thinking process for solving both types of problems, scientific and everyday problems, may be very similar (Johnstone, 2001). Indeed, students in general have difficulty transferring knowledge and skills among disciplines (Perkins & Salomon, 1989; Johnstone, 2001). There is a great need for innovative studies targeting the sources of difficulties and aiming to develop new strategies to help students transfer their daily problem solving abilities to scientific domains and vice versa. If we want to make students' learning experience more fruitful and efficient, we must consider and study as many variables affecting problem solving as we can and obtain a clearer picture of the kind of abilities needed to be successful in problem solving in chemistry. We must detect where the lack of skill(s) or any other requirement for the successful problem solving exist (Herron & Greenbowe, 1986).

Statement of the Problem

Many students view chemistry as one of the most difficult subjects (Stieff, 2002; Schmidt, 1997, Astudillo & Niaz, 1996). Learning chemistry places many demands on students that can be overwhelming. Instructors frequently present chemical symbols, equations and scientific measurements simultaneously to explain changes at the microscopic level that are not visible to students. Moreover, the "abstract" concepts of chemistry are often seen as limited to the chemistry classroom and not valid and relevant outside of school. As a result, chemistry students may be scared of chemistry. This fear can discourage them and they may lose their self- confidence, which conventional wisdom considers essential to be successful in any area of our lives (including solving chemical problems).

Stoichiometry, one of the many complex topics in chemistry, requires a series of skills, organized knowledge of chemistry, and knowledge of mathematics. Successful problem solving in stoichiometry requires the solver to :

- calculate molecular weight of compounds,
- write chemical equations and balance them,

- have conceptual understanding of the mole concept and the particulate nature of matter,
- determine the limiting reagent,
- calculate mass percent and percent yield,
- deal with ratios, and
- find the empirical and molecular formula.

Although some students have the knowledge of chemistry and mathematics to solve simple problems, they cannot use and link their knowledge pieces to do complex calculations. It seems that their knowledge is composed of isolated facts and separated through different domains. It is widely accepted that students' performance during problem solving is affected by students' knowledge structures (Bedard & Chi, 1992; Chi, Glaser, & Rees, 1982; Gerace, 2003). Students who do not have conceptually organized knowledge have difficulties in solving problems. We also know that students' problem solving performances are influenced by not only the knowledge structure but also the some cognitive variables.

There are different types of cognitive variables. Some are related to students' prior knowledge and some related to students' capacities, abilities, and skills. Although we want to include and investigate all the cognitive variables,

which are cited in the literature as the factors on problem solving, we cannot do because of the time constraint. We believe it is important to consider as many variables as we can as some researchers (Towns & Grant, 1998; Ross & Fulton, 1994; Lyle, 2001) do in order to better understand the complex process of problem solving. In the study, we only examine the influence of the following cognitive variables on the students' achievement in stoichiometric problem solving:

- conceptual understanding of subject matter (particulate nature of matter and mole concept) (Nakhleh & Mitchell,1993; Phelps, 1996; Nurrenbern & Pickering, 1987),
- formal (proportional) reasoning ability (Dawkins, 2003; Lesh, Post, & Northern, 1988; Akatugba & Wallace, 1999; Kwon, Lawson, Chung, & Kim, 2000),
- cognitive development (Atwater & Alick, 1990; Huitt & Hummel, 2003;Smith & Sims, 1992), and
- working memory capacity (Baddeley, 1986; Stamovlasis & Tsaparlis, 2000; Miller, 1956; Johnstone, 1983; Johnstone & Kellett, 1980).

In parallel with the factors affecting problem solving performance and the effort in understanding the difference between successful and unsuccessful students, we set our goals along with three research questions:

(1) To what extent do the difficulties in solving stoichiometry problems stem from poor understanding of pieces (domain-specific knowledge) versus students' inability to link those pieces together (conceptual knowledge)?

(2) What are the differences between successful and unsuccessful students in knowledge, ability, and practice?

(3) What are the roles of cognitive development, formal (proportional) reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in successful and unsuccessful students' problem solving success in stoichiometry?

Importance to the Field

In my teaching life, stoichiometry has been the one of the most challenging topics for my students and myself. It was difficult for me to teach and hard for my students to understand. When a student really struggles with stoichiometry, they sometimes begin to lose hope of being successful in

chemistry. I have tried many techniques in my classroom to make my students more efficient and successful in solving stoichiometry problems. All the techniques I tried, however, were not satisfactorily effective. I seriously started questioning my teaching ability and techniques while trying to find where I had been making mistakes.

Later, during my graduate studies and, finally, in my literature review, I found out that I was not the only one having these difficulties and feelings. Many teachers have confronted the similar difficulties in their schools. In my literature review, I realized that the problem cannot be resolved easily because the path students should follow to go from wherever they are now to wherever we want them to be is not clear and not straightforward.

Many educators and researchers have examined the steps and processes needed for students to become efficient in problem solving. If we look over the Handbook of Research on Teaching and Learning Science (Gabel & Bunce, 1994), we will notice that there is much more research on problem solving than any particular area in science teaching. The same handbook also indicates that research on problem solving receives more attention by chemistry educators than other science educators.

Problem solving research areas in chemistry have mainly been within a few especially challenging areas (in terms of students' learning) (Gabel & Bunce, 1994). Some of those concepts received attention by the researchers are as follows: *matter and its states* (Osborne & Cosgrove, 1983), *particulate nature of matter* (Novick & Nussbaum, 1981; Harrison & Treagust, 2002; Williamson, Huffman, & Peck, 2004; Dori & Hameiri, 2003), *molarity and solutions* (Gabel & Samuel, 1986; Ebenezer & Erickson, 1996), *chemical change* (Ayas & Demirbas, 1997), *heat and temperature* (Erickson, 1979), *chemical equilibrium* (Chiu, Chou& Liu, 2002), *acids and bases* (Nakhleh & Krajcik, 1991) , *mole concept* and *stoichiometry* (Gabel & Sherwood, 1984; Duncan & Johnstone, 1973; Boujaoude & Barakat, 2000; Wolfer & Lederman, 2000; Astudillo & Niaz,1996).

Although the number of studies on problem solving in chemistry is comparatively very high, there remains ample need to make students better problem solvers. There are still many students who are about to take stoichiometry who are afraid of it, and many who are currently taking it struggle a lot with it (Felder, 1990; Wolfer & Lederman, 2000; Gabel & Bunce, 1994). The homework seems to never end, and students sometimes spend hours on a single problem without getting an answer (Felder, 1990).

The goal of my research is to explore the students' problem solving performance in stoichiometry in depth, find the reasons behind the difficulties that students encounter while solving the stoichiometry problems, and to produce more effective methods to make students more successful problem solvers in stoichiometry and maybe in other chemistry problems.

CHAPTER II

LITERATURE REVIEW

During the literature review, I have read many articles and books about problem solving in chemistry and other disciplines. The most common comment about the research on problem solving is that doing research on problem solving is very challenging due to a few reasons such as unclear definitions, mysterious problem solving process, numerous variables affecting problem solving, and difficulty of controlling or observing the factors influencing the success in problem solving. Due to these factors, researchers perceive studying problem solving as a very difficult and challenging task to complete successfully (Green, 1966).

I will structure this literature review around the following questions:

- Why is chemistry perceived as a difficult subject to study?
- What are the characteristics of chemical problems?
- How are experts different from novices in terms of their problem solving performances?
- What are the factors contributing to the differences between experts and novices?
- What are the factors influencing the problem solving process?

- How should I design my research so that I can learn more about the sources of the difficulties that students encounter while solving the stoichiometric problems and understand better the problem solving process at all?

In the following sections, you will find some of the answers I found in the literature on problem solving and several explanations illuminating the difficulties that students have while learning chemistry. Along the way, I will account for the reasoning behind my research questions, design, and subject selection using the arguments found in the literature.

Chemistry and its Complexity

Chemistry is indeed a challenging discipline that demands good understanding of several concepts and involves a mental transfer between different types of representations (Gabel, 1998; Pinarbasi & Canpolat, 2003). Many chemistry concepts are interconnected and are built upon previous knowledge. The learner needs to develop a conceptual understanding, which necessitates the linking of several knowledge pieces and different modes of the representations reflecting the changes that matter undergoes. This aspect of chemistry makes learning chemistry hard for some students (Plesch, 1999).

Chemistry at Macro, Micro, and Symbolic Levels

Chemistry learning requires linking among macroscopic, microscopic, and symbolic representations. Hoffman and Laszlo (1991, p.9) define chemistry by pointing to its interrelation with macro and micro world:

> Chemistry… is a mix of molecular engineering, based on extrapolations from macroscopic, and a science, coming to grasp directly with microscopic.

A very important requirement for being a chemist is having a good understanding of each type of the representation, linking them, and using those representations across tasks and contexts (Dori & Hameiri, 2003).

Johnstone (1991) suggests that students have to study chemistry concepts at three levels in order to have conceptual understanding of chemistry and avoid rote memorization of rules and formulas. The first is the macroscopic level, which is related to observable changes. The second is the microscopic level, which is related to particles. The third is the symbolic level used to represent the changes using chemical symbols and formulas.

The studies referenced in Gabel's review (Gabel, 1998) indicate that students have difficulty understanding chemistry at macro, micro, and symbolic levels. A lack of linking among these three distinct levels and relevant concepts results in difficulties for students to interpret and explain the chemical changes. Students' difficulties can also be attributed to students' incomplete or inappropriate mental models for atoms and molecules

and the fact that particles (atoms and molecules) are invisible to the naked eye (Gabel, 1998).

Dori and Hameiri (2003) also pointed out that students have a hard time seeing the connection between abstract chemical symbols and chemical changes observed at macroscopic level but actually takes place at microscopic level. A learning environment should be designed in a way that helps students to appreciate each level and see the connections among representations at the macroscopic, molecular, and symbolic levels.

All chemical educators are aware that this is a challenging task to accomplish. Although many educators are pleased with students' engagement while watching macroscopic chemical events such as simple demonstrations (ammonia fountain, volcano, crushing pop cans, and boiling at lower temperatures, etc.), they are challenged to sustain students' interest at the submicroscopic and symbolic levels and help them to comprehend the principles behind chemical events at macro level (Harrison & Treagust, 2002).

Chemistry educators should emphasize on the particulate nature of matter and its interrelation with macro and symbolic levels and then help their students learn this fundamental knowledge, which is essential for effective chemistry problem solving and to understand the nature of everyday phenomena.

The Significant Characteristic of Chemistry: Particulate Nature of Matter (PNM)

The principle that pivots on the belief that matter is made of invisible particles and changes observed at macroscopic level can be explained by microscopic terms is one of the significant premises of the chemistry. People have been talking about the particulate nature of matter for centuries. At very early centuries, Greek people started to explain everyday observations like growth and decay using the particulate nature of matter. Greek philosophers like Aristotle and Democritus were aware that a particulate theory is a powerful way to account for many natural phenomena. Democritus suggested that certain changes could be explained by the idea of tiny indivisible particles of matter, which could not be directly observed by the senses.

Research (Williamson, Huffman, & Peck, 2004) has indicated that understanding the particle model will provide the learner with many benefits, such as a better comprehension of chemical concepts, such as mass conservation during phase change, heat and temperature, and solutions and more effective problem solving skills. In addition, according to AAAS (2001), realizing that matter is made of tiny particles helps students gain one of the important principles of science literacy.

Recent studies also show that the failure to appreciate the importance of the particulate nature of matter in understanding of chemical concepts such as the mole concept and chemical reactions results in misunderstandings in chemistry (Gabel & Bunce, 1994; Dori & Hameiri, 2003). Lacking deep understanding of the particulate nature of matter causes difficulties in the subsequent topics and encourages dependence on memorized techniques. Studies indicate that stoichiometric relationship between atoms, molecules, and reactants and products are not recognized well (Dori & Hameiri, 2003).

In the following section, I will give examples of how the particulate nature of theory is connected to other chemical concepts and how crucial it is to know and use it to explain the observable phenomena.

Interrelation between PNM and Other Chemical Concepts

The comprehension of the particulate nature of matter is essential for learning chemistry concepts such as the states of matter, temperature, and heat (Valanides, 2000), understanding mass conservation during physical and chemical changes (Tuncer, 2003), explanations of atomic structure, bonding, molecules, and chemical reactions (Harrison & Treagust, 2002). The understanding is also essential for grasping the nature and importance of everyday phenomena such as melting of ice and dissolution of substances.

The explanatory power of particle model is also the basis of understanding for other chemistry-related topics such as acid-base reactions, solubility, and chemical energy (Harrison & Treagust, 2002). I have taught a physical science course for elementary teachers and we have always used the particle model to explain challenging phenomena, such as why water boils at lower temperatures on mountains, why a soda pop can containing water vapor crushes after transferring the can to a container filled with ice-water mixture, and why the weight (but not mass) of a balloon containing dry ice lowers as the dry ice transforms into carbon dioxide (a buoyancy effect). I can certainly say that we have always benefited from using the particle model and have experienced its profound explanatory power. My experience is corroborated by de Vos and Verdonk (1996) who pointed out that in educational research as well as elementary science education, the particulate nature of matter is associated with the fundamental topics taught at elementary level, such as solids, liquids, and gases and phase transitions; diffusion and dissolution processes; heat and heat transfer; electric currents.

Indeed, a vast array of biological, chemical and physical phenomena can only be explained by understanding the changes in the arrangement and motions of atoms and molecules (Harrison & Treagust, 2002). Thus, science educators should assist their students to comprehend the particulate nature of matter and help them to use this theory not for only science problems they

are dealing in the classroom but also for many natural phenomena they observe in everyday life.

At the same time, we note that the learning and teaching particulate nature of matter has some difficulties. Teachers complain that their students do not always understand the particle nature of matter at a level they want (Dori, & Hameiri, 2003). Students exhibit limited understanding of the particulate nature of matter and have difficulties in recognizing the particle nature of matter in observable phenomena. We desire to find the sources of these in order to better deal with them.

Difficulties with Teaching, Learning and Using Particulate Theory

There are several difficulties regarding the teaching, learning, and use of particulate nature of matter. One of the common problems I have observed in my classrooms is that students do not use the particle model unless they are explicitly told to do so. If a question contains even minimal particulate terminology, students will tend to answer in particulate terms. On the other hand, when questions are phrased using everyday language, students will use everyday and macroscopic terms to answer the questions. Research (Williamson, Huffman, & Peck, 2004) indicates that students are cued immediately when the particulate theory words like atoms or molecules are used in the questions.

Studies (Williamson, Huffman, & Peck, 2004) in the area of students' alternative conceptions have indicated that isolating school science from students' real-life could make students develop two unconnected knowledge systems related to science: one is used to solve science problems in schools, and the other used for everyday life. Lewis and Linn (1994) found that encouraging students to combine their experiences in the everyday world with scientific examples and explanations helps to prevent compartmentalization.

In order to avoid the compartmentalization of knowledge, the particulate model should be used to explain the macroscopic phenomena. As students use the particle model and make sense several macroscopic observations to themselves, they will enjoy more employing the particle model. For example, at the macroscopic level, students often talk about dissolving but they cannot differentiate it from melting. They think that when sugar dissolves, it becomes water or liquid sugar (Valanides, 2000). However, when they are encouraged to think at micro level and explain this phenomenon using the particle model, they realize that their previous thinking is deficit and eventually change their previous explanations into scientific ones, which help them to see theoretically, what changes take place as sugar dissolves in water (Valanides, 2000).

Research (Bunce & Gabel, 2002) also shows that comprehending the particle model takes a long time and it is mostly evolutionary. Therefore, the

particulate model should be introduced at early stage of childhood and should continuously be taught throughout the learners' education. Then, we can hope that this model will be an important part of their knowledge system.

The difficulties in using the particle model are not limited to the compartmentalization of knowledge. We have much more serious difficulties such as misconceptions, which are more challenging to overcome. Most students inductively learn something about particles, atoms, and molecules from several sources such as TV, radio, magazines and newspapers before they go to school. Unfortunately, these sources of the knowledge lead children to misconceptions. These misconceptions include 'air is nothing because gas particles do not occupy space and do not have mass', 'matter can be divided endlessly', 'mass changes as phase changes', ' taste, color and other properties of particles are the same with the properties of the substances they are in', and 'atoms might be visible with good microscopes' (Harrison & Treagust, 2002). Obviously, it is more difficult to teach a concept when a misconception needs to be corrected. By analogy, I know from my experience that learning a word's right pronunciation is more difficult if you learned it wrong at first.

Another source of the misconceptions and students' insufficient understanding of particulate nature of matter might be the conventional lectures. Research (Bunce & Gabel, 2002) indicates that conventional lectures do not provide a sufficient understanding of the particulate theory for students to account for observed macroscopic phenomena. Telling the

students matter is made of particles, which are invisible, might not help students to have comprehensive understanding. Researchers (de Vos, & Verdonk, 1996) believe that students cannot comprehend the particulate nature of matter without understanding of the meaning of the scientific argument at the same time. Students are not generally provided with sufficient empirical data about particle model and do not find enough chance to discuss about the nature of atoms and molecules until they start their college education yet we expect them to bring explanations at the micro level (Harrison, 2002). There are very vital questions such as "What evidence do students have to believe that matter is made of invisible and continuously moving particles?" and "What are the advantages of believing the existence of those tiny particles called atoms or molecules?". Such questions need to be answered to make this part of chemistry less difficult and more fruitful for students, so that they can develop a comprehensive understanding of chemical concepts.

Like conventional lectures, traditionally written textbooks do not provide meaningful learning of the particulate nature of matter. On the contrary, in these textbooks, memorization of useless facts are implicitly promoted. Until recently, college chemistry textbooks contained very limited evidence for the particulate nature of matter. Although Dalton's atomic theory is important for understanding many other chemical concepts, textbook authors used to present it in a descriptive way rather than

explanatory way (Harrison & Treagust, 2002). Contemporary authors, however, emphasize more on explanatory power of Dalton's atomic theory rather than just listing his postulates (Goldberg, 2007; Bauer et al., 2007). Describing Dalton's theory only encourages students memorize useless facts. For a long time, students were implicitly encouraged to memorize postulates rather than investigating and questioning them.

Unfortunately, the difficulties with teaching and learning of the particulate nature of matter are not limited to misconceptions, compartmentalization of knowledge, and conventional lectures and textbooks. There are more reasons such as spatial ability of students (Bunce & Gabel, 2002), faulty reasoning of students, and informal meaning of words for students' poor understanding of the particulate nature of matter (Maskill et al., 1997; Harrison, 2002). The different meanings of the words can sometimes be problematic while communicating in science classrooms as it is in everyday situations. Students sometimes do not get the scientific meaning of the words since they load different meanings to the same words in making sense of their everyday experiences (Maskill et al., 1997). Another cause for students' poor understanding of particulate nature of matter is cited as faulty reasoning (Harrison, 2002). Students reason from large to small and use the properties of substances to guess the characteristics of particles. The scientific reasoning, on the other hand, works the opposite way and uses the nature and motion of particles to account for the macroscopic events

(Harrison, 2002). For this reason, students think that carbon atoms are black like coal and iron atoms are shiny like metals. They think that atoms have the similar characteristics of the matter we observe or feel at the macroscopic level. When students touch a metal they fell that it is hard and they conclude that iron atoms are hard, too.

It is clearly seen that there are so many challenges and difficulties in learning chemistry and, in particular, the particulate nature of matter. I cannot naturally cover all the aspects of these difficulties and challenges here but we know that the deficiencies in teaching and learning of the particulate nature of matter bring difficulties in understanding of concepts and in representing changes at macro, micro, and symbolic levels and make problem solving in chemistry difficult.

Defining Problem and Problem Solving

One might suppose the intended meaning of words can be transferred from teacher to student, from student to teacher, or from author to the reader without any difficulty, yet often the ambiguity of the words prevents this transfer (Crago et al., 1997). In order to eliminate or lessen such a misinterpretation people should be explicit about the meaning of the words they use, particularly in scholarly research. If we want to study problem solving scientifically, we should define “problem” in such a way that

"problem" is distinct from other types of tasks. Before attempting to discuss different meanings of problem and problem solving, it is wise to consider definitions of "problem" used in literature.

In the literature, I could not find a consensus definition of problem or problem solving. There is considerable diversity in describing what problem solving actually is. Some define problem as a name as it is found in dictionaries, some define status of a problem as subtle interaction between the task and the individual struggling to find a solution (Bodner, 1987), and others point out the difficulty of defining "problem" by confessing that "problem is a bit like beauty, morality, and good art. We are in favor of it, we know it when we see it, but we cannot define it." (Hunt, 1994, p.215).

Towards a Unified Definition of "Problem" and "Problem Solving"

The lack of a universal definition of "problem" and "problem solving" stems from two reasons (Bodner, 2002). The first reason is that educators are not aware that a difference exists between their definition of "problem" and others' definition of problem and problem solving until they have discussion with a colleague or carefully examine their students' learning deficiencies (Bodner, 2003). The second one is that the most researchers were happy with their own definitions of problem because their studies were consistent with their own definition.

The differences in the meanings of "problem" and "problem solving" influence researchers' observations and interpretation of results. Bodner (1991, p.1) shares his observation illuminating one of the possible outcomes of having different meanings of "problem":

> Smith reported that he had fought with Don Woods about whether successful problem solvers most often used a forward-working versus means-ends approach to problem solving. He then noted that the confusion was resolved when he realized that Woods does not consider the solution of exercises to be problem solving.

It should be noted that researchers usually do not give the definition of the problem; rather they define the problem solving process. I think, they implicitly assume that reader may reach a definition of "problem" through reading and understanding of the definition of "problem solving" that they provide in their papers.

Problem solving to Nickerson (1994) is the same as "thinking" and that thinking may be done for solving a problem or about a subject without having any particular problem in mind. In other words, "problems" are not always posed for a solution; they can be asked to advance inquiry and deep thinking (Hunt, 1994). "Problem solving" for Hunt (1994) is an example for any higher intellectual activity.

In addition to Nickerson and Hunt, Woods (1987) also describes problem solving as the mental process that we use to reach the best answer available to an unknown or some decision. He expands his description of problem solving, however, by adding a new dimension. Woods (1987) thinks

that a true problem situation is the one, which is unfamiliar to the problem solver. He cannot recall a procedure right away to carry out the solution. His solution involves a lot of struggle and confusion. In a later paper, Woods (1989) claims that solving a problem requires the problem solver to transfer of knowledge and skills to a novel situation s well.

With a related perspective, Breslow (2001) associates problem solving with learning and creativity. According to him, problem solving has three different steps or aspects, “learning”, “problem solving”, and “creativity.” In Breslow’s schema, *learning* refers to the students' ability to demonstrate their knowledge and skills in familiar contexts and problem solving is a mental activity that problem solvers do when they need to use their knowledge and abilities in somewhat unfamiliar situations or if they do not know how to overcome a challenge by using the learning. Here, we see that Breslow also emphasizes the “transfer of learning” in defining problem solving, in addition to including “creativity” in his definition.

This brief review indicates that problem solving can be seen from different angles. Some see problem solving as almost synonymous with thinking. Others see problem solving as a particularly complex form of learning that has to be preceded by simpler forms of learning (Perez & Torregrosa, 1983). All of these ideas about problem solving provide insight but there is no agreed upon definition as Bodner noted (1991).

Considering the body of literature, there are a few common characteristics in the definitions of problem solving: existence of initial and final state, existence of distance between these two states, difficulty of using knowledge, and, most importantly, existence of uncertainty about what to do. Hayes (1981, p.i) offers a simple definition that combines all those characteristics. He also stresses the interaction between problem and problem solver in this definition:

> Whenever there is a gap between where you are now and where you want to be, and you do not know how to find a way to cross that gap, you have a *problem* and the *problem solving* is what you do, when you do not know what to do.

This definition makes a distinction between two related concepts: exercises and problems (Bodner, 1991). These two tasks are the most common tasks that people often come across in their everyday and academic lives. The common thing for these tasks is that both involve a gap. If we are certain about what we need to do to cross that gap, then we are doing an exercise, not a problem. When we do not see an obvious way to cross the gap, we have a problem.

Examples and Non-Examples of True Problem: Problems versus Exercises

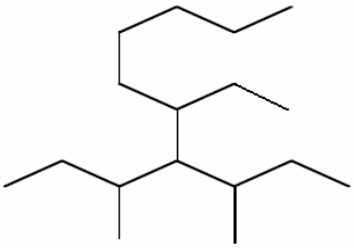
In much of the chemistry problem solving literature, a distinction is made between exercises and problems (Bodner, 1987, 1991; Frank, Baker, &

Herron, 1987, Lyle, 2001). Problems are differentiated from exercises based on the definition of Hayes (1981) and the interaction between task and the individual struggling to find a solution. According to Hayes' (1981) definition, problem means a task where the strategy to reach an answer is unknown at the beginning. On the contrary, an exercise is a question where the procedure is known for the solution already. Thus, we should know about the cognitive abilities, experience, and understanding of subject matter of the person struggling to find a path to cross the gap before we classify a task as a problem or an exercise. Status of a question can be determined best when we have information about the individual attempting to solve the question (Bodner, 1987, 1991). For example, the following question is a problem for most students when they begin their study of chemistry, but a routine exercise for their instructors.

> How many grams of hydrogen will be produced when 10 grams of Mg is reacted with the excess amount of HCl?
>
> $$Mg\ (s) + 2HCl\ (l) \rightarrow MgCl_2\ (s) + H_2$$

The following example is from organic chemistry. It is an exercise for organic chemists but a problem for novices.

> Name the compound shown below using the IUPAC rules.



Besides the distinction between exercise and problem, there are also differences between the strategies used to solve them. Problems, in general, are solved using irrational, irregular, and illinear methods whereas solutions of exercises usually require straightforward, ordinary, and more rational strategies (Bodner & Herron, 2002). Bodner (2003) claims that Polya's method which includes four steps, (1) understand the problem, (2) devise a plan, (3) carry out the plan, and (4) look back, is a more proper method for generic exercises while his *anarchistic model* (Bodner, 2003, p.28), which was generated using Grayson Wheatley's (1984) model, is promising more success for problems :

> (1) Read the problem, (2) Now read the problem again, (3) Write down what you hope is the relevant information, (4) Draw a picture, make a list, or write an equation or formula to help you begin to understand the problem, (5) Try something, (6) Try something else, (7) See where this gets you, (8) Read the problem again, (9) Try something else, (10) See where this gets you, (11) Test intermediate results to see whether you are making any progress toward an answer, (12) Read the problem again, (13) When appropriate, strike your forehead and say, "Son of a ...", (14) Write down *an* answer (not necessarily *the* answer), (15) Test the answer to see if it makes sense, (16) Start over if you have to, celebrate if you don't.

In addition, one limitation of Polya's model is the assumption that we begin the problem by understanding it. According to Dewey and Wheatley (cited in Bodner, 1991), this is not true. They claim that understanding of the problem arises toward the end of the problem solving process.

The Influences of Distinction between Problem and Exercise

Like in other disciplines, in chemistry, students' low success rates are attributed to their poor performance in problem solving. This failure, by teachers, is often related to students' lack of declarative knowledge and poor mathematical skills. This stance, however, implies a belief that problems are seen as simple exercises (Perez & Torregrosa, 1983). Unfortunately, students generally do not learn strategies need to be followed to solve problems but tend to memorize solutions explained by the teachers while they are solving questions, which are exercises to themselves but problems for their students (Perez & Torregrosa, 1983). Students often forget the fact that their instructors usually practice solving the same sort of questions many times before they solve the question on the board for them. Those questions are not counted as problems any longer for their instructors (Perez & Torregrosa, 1983). This is why instructors seem to be very fast and accurate. This lack of awareness causes students to use inappropriate strategies while attempting to solve the same type of questions, which are exercises to their instructors but problems to the students.

Students, who do not see the difference between the problems and exercises, might treat them the same way and seek for a strategy and an algorithm that seem promising in providing the best answer. The same students do not think that having an algorithm or a strategy ready is not

always sufficient for solving a problem because problem solving is “what we do when we don’t know what to do”. A problem solver focuses on all details in the problem, attempts to interpret the given information at different levels, micro, macro, and symbolic level, and most importantly needs to spend considerable amount of time to understand what the problem is really asking. On the other hand, an exercise solver first writes down the equations and formulas just after reading the question (Frank et al., 1987). When students are not aware of the distinction between exercise and problem, it affects their attitudes and success in problem solving.

The role of the solver in determining what is an exercise or problem poses a difficulty for research comparing experts and novices. In particular, using the same questions to analyze the problem solving skills and performance of experts and novices is problematic. The questions used in the research might be true problems to novices and simple exercises to experts. And so, the studies aiming to compare the performance of experts, who are usually faculty or PhD students and have an extensive knowledge in the field, to that of novices, who are undergraduate students and naïve in the field, need to be extra careful while choosing the questions for the study. The difficulty of questions should be adjusted in a way that demands more than recall from the experts and gives the novices a chance to show their knowledge and ability in the solution (Smith & Good, 1984).

In light of this difficulty, in this dissertation research, I did not choose my subjects within two extreme groups, experts and novices. Rather, I chose my subjects among undergraduate students taking the same general chemistry course and grouped them as successful and unsuccessful ones based on their stoichiometry test results (Camacho & Good, 1989; Heyworth, 1999).

Identifying Problem Solvers

Defining or Distinguishing Expert and Novice Problem Solvers

I do not think it is appropriate to define simply the meaning of experts and novices by looking them up in the dictionaries. Rather, we should investigate the behaviors and activities of good and poor problem solvers and then we may describe experts and novices' characteristics, respectively. These definitions are working definitions. In research, experts are usually defined and chosen among PhD students and professors. However, I think that being a PhD student does not necessarily mean being an expert. Even if some PhD students are classified as experts, I do not think that all will be at the same level. As there will be differences between professors and the graduate students in terms of their expertise, graduate students will certainly have differences among them. All these details indicate that there is a need for

developing new ways to define the experts and novices, introduce the levels in the expertise, and detect better methods to differentiate novices from the experts.

I do not actually know how to categorize experts and how we can draw a border between novices and experts. To determine after what level or what point novices become experts is a challenging or, maybe, an impossible task. We do not have a measurement tool to differentiate clearly experts from novices. This makes research aiming at finding differences between experts' and novices' strategies and performances harder than expected. In literature, I tried to find as much information as I could about the characteristics of experts and novices so that I could use it as the criteria to distinguish the experts from the novices. Although experts and novices have some distinct features, some of the characteristics and approaches are common for both groups. I do not think we can really separate their general characteristics and their approaches from each other completely. Therefore, you can find some characteristics of experts in novices' characteristics and some novices' characteristics in experts' characteristics.

Characteristics of Expert and Novice Problem Solvers

There are number of characteristics that can help to differentiate the expert problem solvers from the novice problem solvers but the most

important one is that experts qualitatively analyze the problem and consider it as a whole not to miss any important interaction among the different parts of the problem. They tend to categorize problems according to their fundamental principles and determine the groups to which problems belong before deciding what strategies need to be followed to carry out the solution (Maloney, 1994; Marshall, 2003; Glaser & Chi, 1988). Another important characteristic of experts is that they plan their work before attempting a solution while novices' solutions show a lack of planning. They immediately write down the equations after reading the questions, jump right in to the solution, and usually follow the algorithmic means to solve problems (Breslow, 2001; Larkin, 1979; Larkin et al, 1980; Easton & Ormerod, 2001).

Larkin et al. (1980) observe behaviors of experts and novices working typical kinematics problems. During problem solving, novices see their task as recalling algorithms and rules that have worked for them before and applying them to get an answer. I feel, in this respect, they are *rule learners* (Larkin et al, 1980). Novice problem solvers' methods also appear unstructured and inefficient. They cannot handle the problems systematically and solve the problems mostly without units (Larkin at el., 1980).

Mysterious Journey to Becoming an Expert

How do novices, who are very different from experts, become fluent and successful at solving problems like experts and acquire the features of good problem solvers? Is there a way to determine the method or road, which they follow to become experts?

deGroot (1978) attributes chess master' quick recognition of chess configurations to their knowledge acquired over tens of thousands of hours of chess playing against their opponents. Experts are able to retrieve flexibly important facets of their knowledge with little effort. One of the important goals in learning is to become fluent at recognizing problem types in particular disciplines and topics--such as problems involving equilibrium, chemical rate and stoichiometry--so that students can retrieve appropriate solutions from their memory. Novices, however, usually cannot either recognize problem types or understand what questions are really asking. Recognizing the problem type and understanding the question are very important steps in solving problems in chemistry and other disciplines. To gain these abilities and be familiar with problem types, students might need more time, more examples, more exercises, or new techniques. Ryan (1987, p.524) also focuses on the positive effect of problem recognition on experts' problem solving:

> Indeed, this act of recognition and recall occurs so rapidly that it appears intuitive. The authors suggest that a similar process accounts for the apparent ease with which an expert solves problems in physics, rapidly selecting appropriate facts, formulas, and procedures. Furthermore, the process of recognizing and naming sub-steps may be important in solving complex problems.

Encouraging students to break down the whole problems into sub-steps and write them down can help students recognize them and improve their performance on more complex problems. Several researchers (Bransford, Brown, & Cocking (Eds.), 2002; Segal, 2005) have concluded that it takes a long time and requires a lot of training for a novice to become an expert in one single field. In order to become experts, students should solve a sufficient number of true problems, which are unfamiliar to them (Gendell, 1987; Johnstone, 2001).

Perhaps, when students fail, they have not dealt with all sorts of problems and topics enough to recognize the types of problems. There is still a long way for them to travel to become experts as we have defined their characteristics in detail. In the short run, however, we can make our students more successful even if we cannot make them experts quickly. For this reason, I think, we should also study and know the differences between successful and unsuccessful students, successful and unsuccessful problem solvers.

Characteristics of Successful and Unsuccessful Problem Solvers

There are some researchers (Camacho & Good, 1989; Smith & Good, 1984; Bodner & Domin, 1995; Heyworth, 1999) studying problem solving classify problem solvers as *successful* and *unsuccessful* problem solvers instead of experts and novices and investigate their differences accordingly.

Successful students are able to recall the specific strategies and pieces of knowledge necessary for the solution of the question. Unsuccessful students cannot make connections easily between what they have learned and the information given in the questions especially when students are not familiar with the type of the questions. Successful students are careful and make fewer mistakes while carrying out the solution. On the contrary, unsuccessful students jump right into a problem without thinking about all the aspects of the problem and do more errors while performing the calculations. The high number of errors and lack of planning in unsuccessful students' solutions might be attributed to the fact that unsuccessful students' knowledge is fragmented and unorganized. On the other hand, like experts, successful students have an organized knowledge base structured around the underlying principles. Unlike unsuccessful counterparts, they think ahead, devise strategies, and modify them as needed (Breslow, 2001; Bodner & Domin, 1995). Successful students also use more symbolic representations while solving problems than unsuccessful students do. Bodner & Domin

(1995) views the use of the symbolic representations as an important requirement for successful problem solving in chemistry.

I believe that possible explanations for the differences between successful and unsuccessful problem solvers is more relevant for education research than comparing experts' and novices' problem solving achievements. Therefore, I did this research choosing my subjects among successful and unsuccessful chemistry undergraduates. Nevertheless, both types of studies will inform our research: those that compare experts and novices and those that compare successful and unsuccessful students.

Understanding the Sources of the Differences between Experts and Novices

It is important to know that experts are different from the novices as well as successful students from unsuccessful students but understanding the sources of the differences between those groups is much more important. It may help us to find out why novice students have hard time in solving stoichiometric problems and show us how we can help novices through their journeys towards being experts. We therefore decided to examine the sources causing the differences instead of staying on the surface and repeat that "yes, experts are different from the novices".

Role of Knowledge Structure

The nature of knowledge structure (i.e. inter-connectedness of knowledge) has great significance on the differences between experts and novices and between successful and unsuccessful students (Bedard & Chi, 1992). We therefore decided to investigate first influence of the knowledge structure on the differences between the groups. To understand the importance and influence of knowledge structure on problem solving, we might consider the following problems. These problems can be classified as difficult and easy questions in terms of required knowledge and skills. These questions are just examples for each type; of course, we can find more difficult and easier ones.

> *Easy question (EQ):* What is the molecular weight of $Al_2(SO_4)_3$? (Al:27g/mol, S:32g/mol, and O:16g/mol)
> *Difficult Question (DQ):* Hydrocarbon mixtures are used as fuels. How many grams of CO_2 (g) are produced by the combustion of 200 g of a mixture that is 25% CH_4 and 75% C_3H_8 by mass (Silberberg, 2006, p.132)?

My students at college and high school level are usually successful while solving the EQ because they just need to know a piece of knowledge (meaning of molecular weight) and basic algorithm to calculate the molecular weight. On the other hand, most of them have a hard time with DQ and usually fail at finding the correct answer. Students need to know a great deal of knowledge related to symbols of elements, writing reactions, balancing the

reactions, mole concept, mass percents, ratios, and algebra. Students have to consider many knowledge pieces simultaneously to be able to solve the DQ. Students are successful when they deal with a piece of knowledge at a time but show poor performance when they are required to consider many pieces at a time. It looks that students do not have organized knowledge and cannot retrieve the knowledge pieces or link the knowledge pieces.

Several researchers (Gerace, 2003; Heyworth, 1999; Bedard & Chi, 1992) have found similar results after their investigations. Novices have poorly structured knowledge, misconceptions, and poor understanding of concepts, whereas experts' knowledge is precise and linked to related procedural knowledge. Heyworth (1999) points out that experts are able to explain and represent changes at macro, micro and symbolic level, but novices generally have difficulty at grasping the particle nature of matter properly, cannot use it efficiently, and often cannot make connections among the representations at these three distinct levels. The study (Heyworth, 1999) also reveals that conceptual understanding of experts differs from that of novices. This difference implies that conceptual understanding is synonymous with having the ability to connect the knowledge pieces around the underlying principles and represent the knowledge at different levels and in distinct forms.

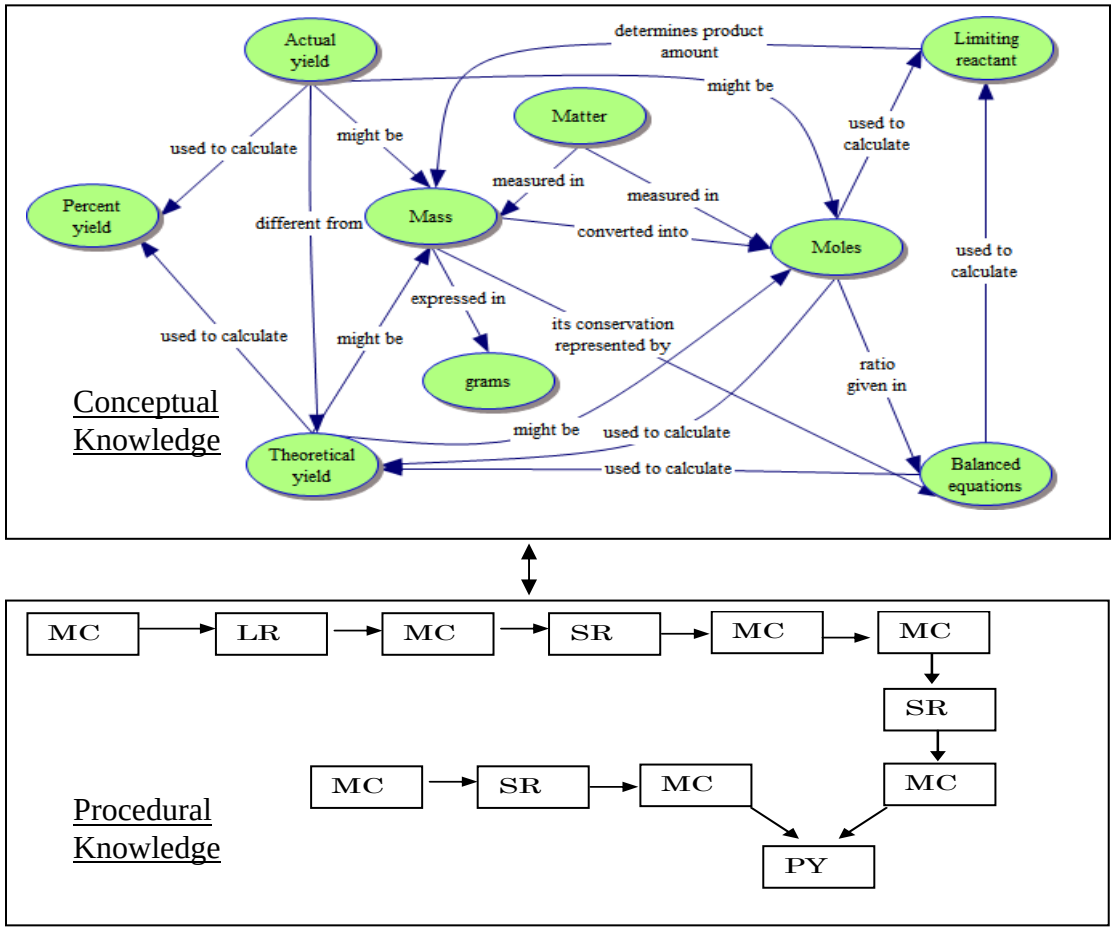


Figure 2.1: Experts' Knowledge Store

The Figures 2.1 and 2.2 represent conceptual and procedural knowledge (specifically for problem 2) possessed by experts and novices, respectively. Note that in experts' knowledge store, the conceptual knowledge pieces are connected with each other and there is a two-way arrow between conceptual knowledge and procedural knowledge. This bi-directional linkage shows that experts continuously revise and modify their conceptual and operational knowledge as they solve problems and learn new pieces (Gerace, 2003). The linkage among the pieces in both types of knowledge has a great importance in solving complex problems because that kind of conceptual

understanding helps experts to see the underlying principles in the problems and retrieve the necessary knowledge as chunks of pieces rather than individual pieces. Retrieval of the knowledge in chunks reduces the load on their working memory capacity and makes them more flexible and efficient with dealing more pieces at a time. Naturally, solving complex problems gets easier for the experts.

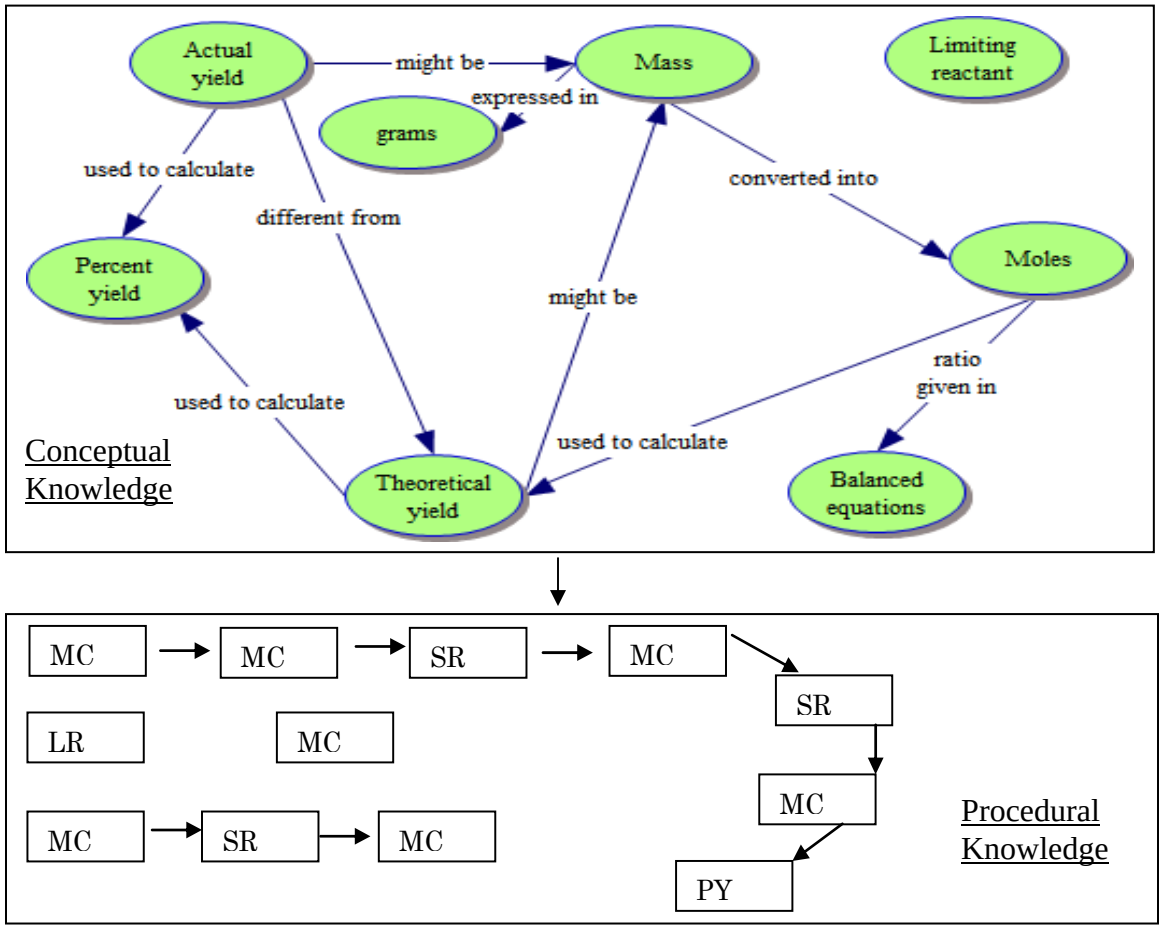


Figure 2.2: Novices' Knowledge Store

In contrast, the novices have hard time dealing with the complex problems because of the heavy load on their working memory capacity. The novices have poor knowledge structuring, weak unidirectional link between

procedural knowledge and conceptual knowledge. Therefore, they cannot see easily the important concepts or principles involved in the questions but the superficial elements such as the name of the compounds, some numbers, or insignificant pieces. They cannot recognize the types of the problems and cannot retrieve the information efficiently since the knowledge is in pieces.

Note that there is a one-way arrow between procedural knowledge and conceptual knowledge compared to the strong bi-directional linkage between the conceptual knowledge and procedural knowledge in experts' knowledge store (Gerace, 2003). The weak linkage indicates that novices use their procedural knowledge to solve the problems but they are not successful in revising and modifying their procedural knowledge.

Another reason for the experts' success and efficiency in retrieval of knowledge is experts' great deal of content knowledge that is structured around the core ideas and concepts in ways that also reflects a conceptual understanding of subject matter (Bransford, Brown, & Cocking (Eds.), 2002). On the other hand, novices' knowledge is fragmented. Novices have a lot of knowledge, but it is compartmentalized, which means that pieces of the knowledge are stored in sealed boxes isolated from each other (Bransford, Brown, & Cocking (Eds.), 2002). This isolation hinders students' creativity and causes poor performance in problem solving. Novices' knowledge appears to be mostly context dependent. Johnstone (2001, p.72) describes this phenomenon as follows:

> Problem solving often depends upon knowledge and experience laid down in memory in such a way as to allow new connections to be made. In contrast, much student learning is laid down either unattached to existing knowledge, or linearly or in a single context. This student had a lot of knowledge, but it was stored in sealed boxes and so was not in a free enough state to allow for the creation of new configurations in new contexts. The way she had laid down her knowledge was firmly bound into fixed contexts. Teachers have the responsibility not only to provide what to learn, but to help their students to revisit the same learning in different contexts and to make the linkages explicit.

Since novices have poor or no connection among the knowledge pieces, they cannot reach easily the knowledge pieces, which are already in their minds, when they need it. For stoichiometric problems as well as for all scientific problems to be solved, retrieving previous knowledge has great importance. As a result of difficulties and errors in organizing of knowledge, many students have difficulty in retrieving necessary knowledge to solve stoichiometry problems.

Since experts have organized and hierarchically structured knowledge, experts know what concepts they need and how they can access the concepts in an optimum way to solve problems in an efficient way. On the other hand, novices have unorganized and ill-structured knowledge, they do not know/cannot identify what they need and how they can find those pieces to provide a promising solution for the problems. Thus, they usually prefer to work backward and use the means-ends analysis to solve the problems.

Hierarchy of Knowledge

The examination of cognitive theories and its applications to problem solving shows that organizing the knowledge hierarchically under core concepts and big ideas makes it more effective and useful (Ryan, 1987). The hierarchically organized knowledge improves students' performance and makes its retrieval much easier.

Reif (1987) and Sirhan et al. (1999) also point out the importance of hierarchical knowledge in increasing students' success in learning and problem solving and assert that knowledge should not only exist but it should also be organized hierarchically for effective problem solving.

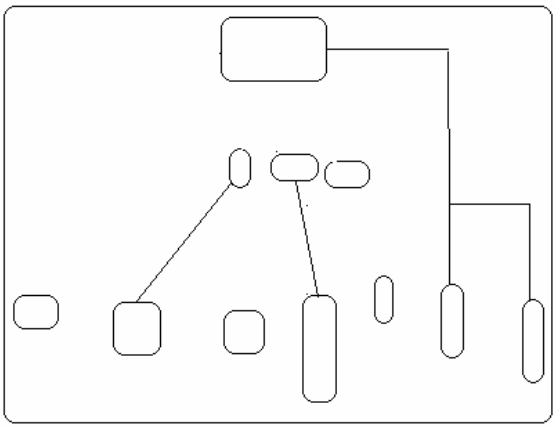


Figure 2.3: Unorganized Knowledge of Novices

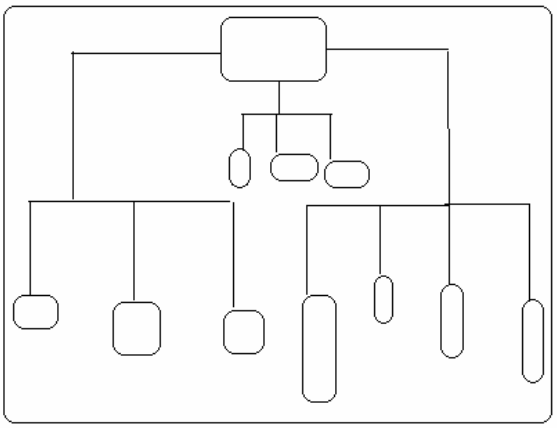


Figure 2.4: Hierarchical Knowledge of Experts

As illustrated in Figures 2.3 and 2.4, novices' knowledge is unorganized, fragmented, and lack the coherency. Instruction should aim to help novices to develop their knowledge into a more organized, coherent, and hierarchical form like shown in Figure 2.4. Knowledge becomes more efficient at

enhancing the retrieval of its pieces when it is stored hierarchically (Pasceralla, 2004; Larkin et al., 1980).

Although we know that having hierarchically organized knowledge has several advantages and benefits, it is not, however, easy for students to put these general principles into practice and transform their fragmented knowledge into a coherent knowledge system (Sirhan et al., 1999). It even becomes more difficult for those students whose prior knowledge has been constructed inappropriately, involves misconceptions or misses the fundamental pieces necessary to grasp the important concepts in chemistry.

Categorization of Knowledge

One of the difficulties students have during the organization of knowledge is miscategorization of concepts (Chi, Slotta, & Leeuw, 1994). Chi et al.'s theory (1994) assumes the novice understanding of a concept is based on a general ontological categorization rather than a phenomenological primitive. Actually, both Chi et al. (1994) and diSessa (1983) agree that novices collect the pieces of knowledge through several sources; nature, books, magazines, journals, lectures, other people, media, etc. The differences come into stage when Chi et al. (1994) and diSessa (1983) start talking about how the novices store the new information pieces and categorize them. diSessa's (1983) theory asserts that novices get their knowledge mostly from the natural events happening around them and they store the knowledge

attached to the specific natural phenomena. Moreover, he (1983) claims that those knowledge pieces are stored in pieces because the novices cannot see the common underlying principles among the different natural phenomena. However, Chi et al. (1994) believe that novices store their knowledge pieces hierarchically under three categories. These categories include matter, processes, and mental states. For example, the things related to plants, animals, solids are stored under matter while the things related to procedures and events are stored under the processes. Since, this is not an easy task, Chi et al. (1994) believe that novices make mistakes while categorizing the new knowledge pieces and put them under the wrong categories. Watson et al. (2001, p. 569) give a good account of Chi et al.'s approach to chemical bonds:

> ….the chemical bonds are often visualized as physical links between atoms. Physical molecular models in which atoms are represented as spheres and covalent bonds as plastic rods holding the spheres together reinforce this view.
>
> Bonding is better represented as a process of interaction: in ionic bonding as a process of interaction between oppositely charged ions and in covalent bonding as a process of interaction between positively charged ionic nuclei and the electrons, which come between them.

As explained above, students are shown plastic rods to represent chemical bonds. As a result, they might categorize bonds and related concepts in the *matter* category and this can cause them to have alternative conceptions about the particle model of matter.

Chemistry students have difficulty categorizing chemical concepts because the new knowledge is not related to their life experiences. Most of the terms in a chemistry class are perhaps heard there for the first time. They cannot use analogies for them because most of the information is too different from their physical world. Students can see paper burning, soda pop is fizzing, and oil floating on water. However, they cannot see the breakage of bonds, formation of new bonds, or transfer of electrons. As a result, they usually have trouble understanding the real reasons causing chemical changes and they do not try to understand what is happening at submicroscopic level. And so, students in chemistry classrooms have great difficulty when categorizing knowledge that is nonsense to them and they cannot use it when it is necessary for solving stoichiometric problems.

Retrieval of Knowledge

Another difference between experts and novices is the level of achievement in retrieval of required knowledge. Being able to retrieve necessary information is an important necessity to be successful in solving all kinds of problems. Some researchers (Miller, 1956; Johnstone, 1993; Bransford, 1979; Huitt, 2003) model the human brain as an information processor to describe how people store, organize and retrieve knowledge.

These researchers claim that there are two main mental processes in problem solving:

1) One is the construction of representations of the problem based on a conceptual understanding of information given in the problem statement,

2) The other one involves the use of a strategy to guide the search for a solution procedure from the initial state of the problem to the desired state.

The same researchers in the information processing area make connections between the working style of brains and computers. In this connection, we find another theory of why students have difficulty and sometimes fail while solving stoichiometric problems. Like the computer, the human mind takes in information, performs operations on it to change its form and content, stores the information and generates responses to it. Thus, processing involves gathering and representing information, or encoding; holding information, or retention; and getting at the information when needed, or retrieval.

Retrieval of knowledge strongly depends on how it was stored and encoded at first place. Researchers (Johnstone, 1993; Bransford, 1979) in the information processing area explain how inability to retrieve knowledge is really a result of not having encoded the knowledge in the first place. Since attention is a limited resource and we can only pay attention to one demanding task at a time, it is easy to find students not paying attention (not encoding) to the key points in learning stoichiometry or any other topic. As a

result, they will not have the pieces fully and will not be able to retrieve them when needed. Some theorists (Huitt, 2003; Baddeley, 1999) contend that we never truly forget anything once it is stored in long-term memory. If that is so, then when we apparently have not retained some information, it must be either the case that we never actually encoded it in the first place, or that the information is still there, but we can no longer retrieve it. Regardless of the reason for students' poor performance in retrieval of the pieces, they will fail in solving the chemistry problems. For example, students need to retrieve knowledge of the chemical symbols and formulas, how to balance the chemical equations, how to calculate the number of moles of the chemicals, and how to use the molar ratio in order to solve the following problem:

> In a lifetime, the average American uses 1750lb (794kg) of copper in coins, plumbing and wiring. Copper is obtained from sulfide ores, such s chalcocite, or copper (I) sulfide, by a multistep process. After an initial grinding, the first step is to "roast" the ore (heat it strongly with oxygen gas) to form powdered copper (I) oxide and gaseous sulfur dioxide. How many moles of oxygen are required to roast 10.0 mol of copper (I) sulfide (Silberberg, 2006, p.107)?

If they are not successful at the retrieval of any piece necessary for the solution of this problem, they will not naturally be successful at finishing their solution and/or will get the wrong answer.

Factors Affecting Problem Solving

One of the main goals in science education is to develop instructional strategies that would improve students' problem solving achievements (Gerace, 2003). However, when we do studies on problem solving and observe what problem solvers do while solving problems it becomes clear that helping students increase their problem solving success is not easy mission to accomplish. We discover that there are so many different methods problem solvers use and there are so many different factors affecting those methods. Unfortunately, no single method promises success in problem solving. Further, it is not possible to claim that today we are even *aware* of all the variables influencing the problem solving. Yet the number of factors we have now allows a detailed and nuanced study.

Teaching vs. Teaching and Learning: Focusing on Students' Knowledge

For centuries, people have investigated to find better ways of teaching subjects in each discipline and have asked the same question: "How can we teach better?" This question naturally affected educators' teaching methods and approaches to learning throughout the world. Educators and researchers from different parts of the world have sadly observed that students did not understand the concepts instructors intended to teach, even after the best

teaching available. Then, educators and researchers started to examine where these deficiencies come from in students' learning. Later, educators realized that they have been asking the wrong question. The question should be "how do students learn better?" rather than "how can we teach better?" because they found that the most important single factor influencing learning is what the learner already knows (Ausubel, 1968).

This caused a paradigm shift in science education. Thus, the people in the field of science education and cognitive science began to find out what affects students' learning and what type of skills and knowledge students should have to be successful in learning and solving problems. After Piaget's contributions (1950), educators better understood that student's minds are not "tabula rasa" –blank sheets- to be filled as Locke claimed in his book, *An Essay Concerning Human Understanding* (1689, reprinted 1995). Students bring their own intuitive knowledge to classroom (McCloskey, 1983; Wandersee, Mintzes, & Novak, 1993). Thus, science educators have investigated pupils' knowledge in depth to understand and change it to address the gap between students' intuitive conceptions and scientifically accepted ones.

Knowledge of Students

A lot of research has been done to reveal the characteristics of students' knowledge. Often the knowledge held by students is contrary to scientific knowledge. These knowledge pieces are sometimes called *alternative conceptions* (Wandersee, Mintzes, & Novak, 1993), *misconceptions* (McCloskey, 1983), *spontaneous reasoning* (Viennot, 1979) or *naïve conceptions* (Caramazza, McCloskey, & Green, 1981). During the past two decades, science education research has focused on uncovering where these alternative conceptions come from and developing instructional strategies to help students revise and correct their misconceptions.

The epistemology of scientific knowledge was studied as well. In these studies, researchers have attempted to find out how knowledge is gained, structured, and used (Gerace, 2003). In addition, hypotheses have been developed to explain why it is so difficult to change the knowledge structures of students. These hypotheses are directly related to theories about how students organize and use knowledge. In order to understand the activity of learning and problem solving process, I think one must know how knowledge is acquired and structured.

There is no consensus among researchers about how to model pupils' knowledge structures. Researchers (diSessa, 1988; Thagard, 1992; Chi, Slotta, & de Leeuw, 1994) give several such modeling methodologies. Since

those investigators interpret students' knowledge in different ways, they naturally propose different techniques to change students' knowledge structures. In the following paragraphs, we will look over different researchers' views (diSessa, 1988; Thagard, 1992; Minstrell, 1992; Chi, Slotta, & de Leeuw, 1994) and see how they interpret the students' learning and knowledge structures and how they account for students' failures in the classrooms.

Students' Knowledge: Fragmented Pieces (Incoherent)

diSessa (1988) is the one of the most important philosophers who believes and supports the hypothesis that describes the students' knowledge as fragmented pieces, which are *loosely* connected conceptions about the natural phenomena happening around them and are used to account for the changes they observe and answer some particular questions. diSessa (1983) calls these knowledge pieces "p-prims" (short for phenomenological primitives). P-prims mostly form in consequence of the interaction with the environment and do not come into stage randomly but are cued by previously experienced or observed phenomena.

In diSessa's (1983) view, which I find to be a plausible model for learning (conceptual change), gaining scientific understanding and knowledge require a major structural change toward coherency. According to this view, the p-prims change their functions in order to be part of the

scientific knowledge and knowledge fragments are structured in a way that produces consistent wholes and promotes successful learning (conceptual change).

In the same line together with diSessa, we can count Thagard and Minstrell, too. Thagard (1992) develops a model called ECHO (Explanatory Coherence) to account for children's knowledge scheme in terms of relations and connections among the knowledge pieces. Learning to him is to modify the connections among the knowledge pieces, make new connections, and change the strength of the connections. These actions are perceived as essential to promote a better coherent and organized knowledge system mostly using the pieces that already exist in the system. diSessa (1983) also thinks that to develop a scientific knowledge, learner needs to build new and deeper systematicity using the knowledge fragments that learner already has rather than attempting to change the pieces one by one.

On the other hand, Minstrell (1992) views students' knowledge- in-pieces and calls them as facets of knowledge or facets of thinking. Facets are students' preconceptions, misconceptions, or ideas related to a natural phenomenon. For instance, in learning seasons learners might say "the closer, the hotter" which means that summers form when the world gets closer to the sun. This idea would be true if the world did not have a tilt, but, of course, it is not true because of the tilt and the angle of the sunshine. Although this type of thinking does not always promise a correct answer, the

explanation cannot be labeled completely wrong. When students link and organize their knowledge pieces appropriately or add new pieces carefully with accurate linking to existing knowledge pieces, they can develop a better conceptual knowledge and bring more scientific explanations.

Students' Knowledge: Organized Pieces (Coherent)

It is today well known and accepted that novices are not like experts nor like theorists in a scientific sense but there is a group of researchers and philosophers (Chi, Slotta, & de Leeuw, 1994; Vosniadou, 1992; McCloskey, 1983) who believes that novices' knowledge system is more coherent than that defended by diSessa and others. The people in this group, basically, assert that novice students possess a coherent, but erroneous reasoning system about the world. According to this belief, novices develop a knowledge system that is comparable to the experts' coherent knowledge scheme.

As opposed to diSessa's theory (1983), Chi, Slotta, and de Leeuw (1994) suggest that the novices' understanding of a concept is based on a general ontological categorization rather than just an arbitrary phenomenological primitive. Chi et al. (1994) attribute coherence to students' thinking and assert that students' learning of a new concept is influenced by their everyday life and culture. Without replacing whole reasoning system and making profound ontological changes, to develop a thinking style as experts have is impossible (Chi et al., 1994). According to Chi et al. (1994), refining p-

prims is not sufficient to generate a coherent knowledge system. The knowledge pieces that are inappropriately structured cannot be refined and transformed into a correct knowledge system by attacking the individual pieces.

Vosniadou (1992) finds that preschool children' thinking about heat, matter, and force is consistent, which supports the hypothesis that children's knowledge scheme is not as fragmented as proposed by diSessa (1983) and others who believe that students' knowledge is mostly made of independent elements.

Researchers and philosophers who perceive students' knowledge system as a coherent and an organized scheme believe that an important educational goal is to develop instructional methods, which cause cognitive conflicts in students' minds and facilitate students' conceptual change by exposing theories with evidence. The cognitive conflict is the first and most important prerequisite in Posner et al.'s (1982) theory of conceptual change as well because they also see pupils' conceptual frameworks as coherent set of knowledge. On a practical level, Posner et al. (1982) listed four conditions that promote accommodation in student thinking: *dissatisfaction* with existing conceptions and development of a new conception, which is *plausible*, *intelligible* and *fruitful*. For cognitive conflict and, eventually, conceptual change to occur in students' minds, they should be encouraged to interact and discuss with each other (Posner et al., 1982).

Explanatory Power of the Theory of Fragmented Knowledge

Both groups of theorists studying pupil's knowledge structures pay attention to students' knowledge structures and aim to change these knowledge structures. They give different descriptions and explanations, however, for existing knowledge structures and the requirements for meaningful learning to occur. I favor the theory of fragmented knowledge because this theory has more explanatory power than the theory of coherent knowledge. The level of knowledge organization can explain the differences between novices and experts.

Novices' thought systems are weakly organized and incoherent while experts have highly structured coherent knowledge structures. When a new p-prim is obtained, it is relatively detached from other pieces of knowledge. As a student's knowledge develops from a naïve state, p-prims become more organized by linking together in a related cluster (Chi, Feltovich, & Glaser, 1981). Thus, experts classify a problem according to its underlying principles, decide to what class of problem it belongs, and solve the problems successfully.

The idea of fragmented knowledge explains why many students still keep their alternative conceptions even after many science classes. Researchers, who believe that knowledge is theory-like, propose that students' knowledge structures as a whole can be replaced with more scientific knowledge structures using methods causing cognitive conflicts.

Research (Clement, 1982), however, has shown that this does not always happen because children have a strong tendency to keep their previous ideas to explain phenomena occurring around them after instruction. This clearly shows that their account for learning and students' knowledge is misleading. If you accept the theory of fragmented knowledge, we will figure out why those students still have alternative conceptions. When we attempt to change their knowledge structure, we are not capable to change whole knowledge structure because knowledge is in pieces. Even if you are able to change some of the pieces, the other pieces will be still in their minds and used by students to explain their world. Therefore, we unfortunately conclude that most of these explanations remain lacking.

Conceptual Understanding and Problem Solving

Science instructors seek for the methods and techniques that can be used to educate students in ways that they can become conceptual learners and successful problem solvers who are capable of applying the fundamental scientific principles to explain the diverse phenomena and solving complex problems encountered in science classrooms and in everyday situations. To make our students good problem solvers we need to understand the interaction between *conceptual understanding* and *problem solving*. Moreover, to understand the interaction between problem solving and

conceptual understanding first we need to define these two processes and find the requirements for both.

Conceptual understanding means the person does not focus on the words, symbols, or formulas but on the meaning they carry and see the ideas or intentions behind them. People with conceptual understanding are very aware that the important thing is not the symbols, figures, or formulas; but rather the concepts they represent. On the other hand, problem solving is simply what we do when we do not know what to do to cross the gap between where we are and where we want to be (Bodner, 1991; Hayes, 1981). While solving problems we need to use several tools and methods. Among the factors affecting problem solving achievement, conceptual understanding – an understanding that is deeper than literal understanding – is perceived the most significant one (Bedard & Chi, 1992). Therefore, I wanted to investigate this interaction and learn more about this factor and how it is related to someone's knowledge system.

The Interaction between Problem Solving and Conceptual Understanding

Instruction in science aims to reach two important goals : (1) making students' knowledge system rich, extensive, and organized in any area and (2) finding ways to enhance students' problem solving success in that area (Gerace, 2003). I believe that there is very complicated interaction between

these two goals and learner or problem solver is in the center of this interaction. The person solves problems better as he learns and organizes his knowledge more effectively and the same person learns more meaningfully as he solves the problems. Learning through problem solving occurs by applying and interpreting conceptual knowledge. For example, when you solve a familiar problem, you will use your conceptual knowledge with its current situation without extra effort but when you solve an unfamiliar problem you need to see new connections among your knowledge pieces and this will result in better conceptual and organized knowledge.

Success in problem solving is mostly based on two types of knowledge; procedural knowledge (algorithmic ability) and conceptual knowledge (conceptual understanding). It is the conceptual understanding that assists the problem solver to restructure the givens in the problem, construct his own representation of the problem, and find a promising strategy to solve the problem by matching the pattern and conditions specified in the problem with the ones already stored in the problem solver's mind. Experts' achievement in the recognition of patterns and interpreting different aspects of problems that can lead to successful solutions can also be accounted for by their better conceptual understanding of subject matter (Phelps, 1996). Considering the fact that conceptual understanding requires the learner to have a coherent and structured knowledge base, to be a good problem solver one must have organized knowledge system.

Chemistry teachers should strive to convey the importance of conceptual problem solving to their students and work harder to close the gap between students' conceptual and algorithmic problem solving abilities and success by emphasizing on the importance of conceptual understanding. It is worth developing the new instructional techniques to narrow this gap between conceptual thinking and algorithmic problem solving. Then, the students majoring in science may develop a better conceptual understanding and non-science majors may participate more actively and start appreciating the nature of science. More importantly, the both groups can benefit from the process oriented inquiry based approaches by learning the processes necessary to be successful not only in the science classrooms but also in their future endeavors and careers (Phelps, 1996).

Conceptual understanding may be achieved best when instructors use conceptual questions. I do not mean algorithmic problems are useless but in some cases, they might not be as effective as conceptual questions for building conceptual understanding. Let us consider the following two questions:

> Q1- What is the thermal equilibrium?
> Q2- Two ice cubes are placed at the same time on two different blocks, which were made of iron and wood and sitting in the same room for more than two days. Which ice cube melts faster, the one on the iron block or the one on the wood block? What does that mean in terms of thermal equilibrium? (This question might be asked after getting students' estimations for the temperatures of the objects such as a metal chair and, wooden table or board kept in the same room for a long time.)

The first question requires retrieval of simple facts; whereas the second question requires deep thinking and helps students learn reasoning behind the simple facts. Moreover, conceptual questions enhance understanding of chemical principles and encourage students to think about the ideas presented. I also believe that conceptual questions, which are often prominent in inquiry-based classrooms, are effective for developing problem solving abilities. Students may learn well through questioning and inquiry-based teaching techniques because students in these types of environments explore new dimensions of the facts by considering the questions and discussing them. Despite the importance of conceptual ability, Nakhleh and Mitchell (1993) found that across all levels, there is a gap between first-year chemistry students' conceptual problem solving ability and algorithmic problem solving ability. We need to investigate the sources of this difference and find the better ways to bridge the gap.

Problem Solving without Conceptual Understanding

We feel it is the consensus belief of researchers studying problem solving that students are successful when the question (exercise) is required to apply just a simple algorithm. However, they show very poor performance when the question (true problem) is required them to conceptually analyze the question, integrate algebra and chemistry, and apply their learning in

naïve contexts. For example, after a semester of chemistry instruction, most students become fluent at reciting the gas laws and comfortable and successful at using them in algorithmic questions. However, an investigation of their answers and solutions at a deeper level reveals that the students have not attained this law conceptually. They memorize the facts, rules, and procedures to reach an answer but do not worry about the comprehension of the underlying concepts and principles.

There is a common belief among the chemistry teachers that students who are successful in solving problems have a good conceptual understanding. Nurrenbern and Pickering (1987) reveal that students' success with problems does not always mean that students have a good understanding of concepts. For example, when students are asked what happens to the gas molecules in a tube when temperature decreases, most reasoned algorithmically that the molecules will have less volume due to the ideal gas equation $PV = nRT$ (Nakhleh & Mitchell,1993). We know, however, that regardless of the temperature of the system, gas particles will occupy the whole space they are in. It does not seem that presenting an algorithm and demonstrating the countless problems that can be solved using that algorithm facilitates understanding of underlying concept.

As we mentioned before, there is a gap between the algorithmic problem solving abilities of chemistry students and their conceptual understanding of chemistry (Nakhleh & Mitchell, 1993). This gap has not

been bridged satisfactorily mostly because of chemistry instructors' insistence on using algorithmic questions in their tests and exams and failure to emphasize on the importance of bringing a conceptual explanation in addition to providing a numerical answer (Phelps, 1996). The studies (Phelps, 1996; Nakhleh, Lowrey, & Mitchell, 1996; Chiu, 2001) show that this gap between conceptual understanding and algorithmic success does not exist in chemistry students only at high schools but also at graduate schools.

The typical chemistry instructor does not question the importance and necessity of conceptual understanding for successful problem solving. We should be aware, however, that the conceptual understanding does not guarantee correct solutions. Although their number is very limited, some students cannot solve problems even though they have conceptual understanding of subject (Nakhleh & Mitchell, 1993). This reminds us of the importance of having a combination of skills including procedural knowledge, which is required for successful problem solving. It is important to have the right combination of skills to unlock the problem and solve it.

Cognitive Development and Influence of Knowledge on Learning

Piaget (Huitt & Hummel, 2003, p.2) claims that intellectual or mental development take place in four periods, which have great effect in people's ability to learn;

> i) *Sensorimotor stage* (Infancy): In this period (which has 6 sub-stages), intelligence is demonstrated through motor activity without the use of symbols. Knowledge of the world is limited (but developing) because its based on physical interactions / experiences. …Some symbolic (language) abilities are developed at the end of this stage. ii) *Pre-operational stage* (Toddler and Early Childhood): In this period (which has two substages), intelligence is demonstrated through the use of symbols, language use matures, and memory and imagination are developed, but thinking is done in a nonlogical, nonreversible manner. iii) *Concrete operational stage* (Elementary and early adolescence): In this stage (characterized by 7 types of conservation: number, length, liquid, mass, weight, area, volume), intelligence is demonstrated through logical and systematic manipulation of symbols related to concrete objects. iv) *Formal operational stage* (Adolescence and adulthood): In this stage, intelligence is demonstrated through the logical use of symbols related to abstract concepts. … Only 35% of high school graduates in industrialized countries obtain formal operations; many people do not think formally during adulthood.

I believe advancement to the fourth period is necessary for students to succeed with stoichiometry. If students do not complete their cognitive development to the formal operational stage, they cannot deal with abstract topics. Chemistry as a whole is mostly abstract to students and stoichiometry is one of those abstract topics in chemistry. If students are not ready to deal with abstract and complex structures when they come to classroom to learn stoichiometric concepts, they may have hard time in understanding them and may fail in solving stoichiometric problems. Atwater and Alick (1990) investigated the level of cognitive development of Afro-American students enrolled in general chemistry courses to determine the strategies used by both successful and unsuccessful problem solvers in solving stoichiometry

problems. Results indicated that a higher level of cognitive development might be crucial in solving the problems that are more sophisticated.

Piaget's theory of intellectual development involves three key processes, adaptation, assimilation, and accommodation. Among these three processes, the adaptation and assimilation happen more often. Adaptation is actually the result of assimilation. The *assimilation* is the process along which the child restructures his knowledge system by connecting the new knowledge pieces gained during the child's interaction with the environment to the existing scheme in the light of experience and the nature of existing knowledge system. On the other hand, a*ccommodation*, which happens less frequently than other two processes, is the reaction of the individual who experiences a conflict between the new knowledge pieces and experiences and the nature and characteristics of the existing scheme. In this case, the more fundamental changes in his scheme have to be made and a revision of whole system might be necessary to accept or accommodate the new information (Bransford, Brown, & Cocking (Eds.), 2002). In this respect, if students' prior knowledge about bonds, equations, or mole concept is different from the conceptions accepted by scientific community, they may have difficulty to accommodate new knowledge presented in chemistry classrooms and in all learning environments.

Ausubel' theory (1968) of meaningful learning also focuses on what the learner already knows and its structure. Ausubel (1968) distinguishes

between rote learning and meaningful learning, emphasizing the role in learning of the existing ideas in the learner's cognitive structure: The most important single factor influencing learning is what the learner already knows (Bargellini, 2005). Rote memory is fine for remembering facts, rules, and strategies but not sufficient for understanding the relationships between the concepts and knowledge pieces. Therefore, it is the meaningful learning and conceptual understanding, which involves recognition of the links between concepts necessary to be successful in solving problems not the rote memorization. If meaningful chemistry learning does not occur, students will be unable to link and connect their knowledge pieces to solve complex stoichiometric problems.

The Effects of Proportional Reasoning on Problem Solving

Proportional reasoning is a person's ability to use effectively the proportional scheme. This ability plays a central role in solving stoichiometric problems. Lesh et al. (1988, p.1) defines proportional reasoning and explains its relation with processing information to reach solutions as follows:

> The proportional reasoning is a form of mathematical reasoning that involves a sense of co-variation and multiple comparisons, and the ability to mentally store and process several pieces of information. Proportional reasoning is very much concerned with inference and prediction and involves both qualitative and quantitative methods of thought.

According to Inhelder and Piaget (1964), the proportional reasoning ability is a major component of the individual's mind, which has completed its cognitive development and it is now at the formal operational stage. The proportional reasoning ability helps the individual solve problems involving ratios in chemistry, mathematics, as well as in other disciplines.

Inhelder and Piaget's work (1964) reveals three stages in the development of the proportional reasoning ability, intuitive, concrete, and formal stages. The *intuitive* stage takes place between age 3 and 7 and during this period, the instinctive thoughts guide the child's behaviors and influence his decisions. During the following stage, the concrete stage, which might be completed between age 8 and 12, the child develops the ability of managing two variables in concrete situations and starts an appreciation of proportional relationship between two variables but cannot transfer this ability into abstract contexts. On the other hand, the child during the formal stage, which starts at round age 12, completes his cognitive development and becomes mature enough to deal with proportional relationships. Although the studies (Lesh et al., 1988; Kwon et al., 2000; Inhelder & Piaget, 1964) clearly define the characteristics of the children who have completed their cognitive developments, there is not consensus in the research about the age up to which children complete their cognitive developments.

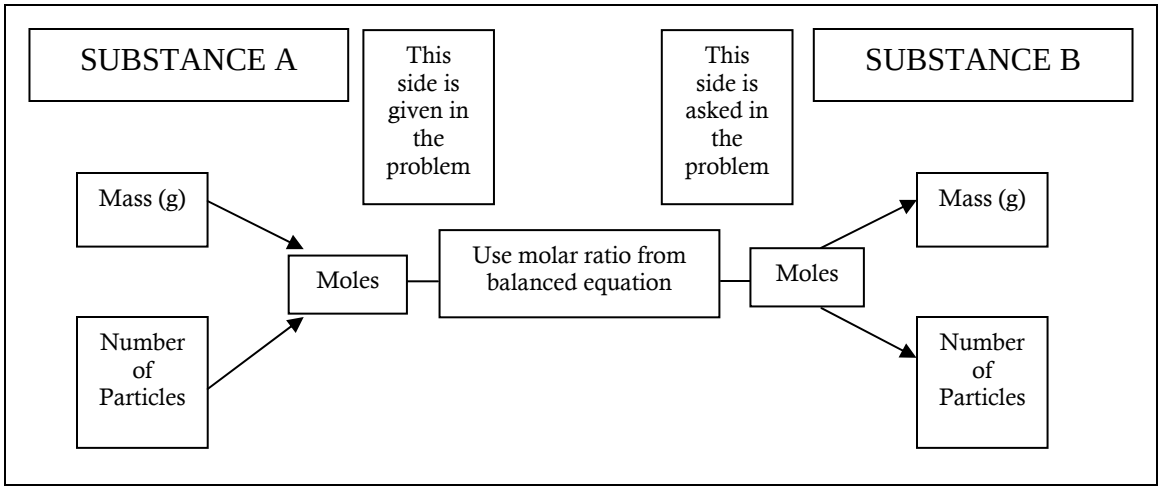


Figure 2.5: A Common Pattern Used for Stoichiometric Calculations

Figure 2.5 indicates a common pattern for stoichiometric calculations. Students need to use their proportional reasoning abilities to go from the number of moles of the substance A to number of moles of substance B. It is crucial to be able to cross that gap by reasoning proportionally. However, experimental evidence has shown that a significant number of college freshmen are not good at using proportional reasoning abilities (McKinnon & Renner, 1971; Ward & Herron, 1980; Wheeler & Kass, 1977).

In the literature, proportional reasoning is implicitly shown as one of the vital requirements in problem solving in science and other contexts (Kwon et al., 2000). The significant relationship between students' proportional reasoning abilities and their success in solving problems has been observed in several studies (Dawkins, 2003; Lesh, Post, & Northern, 1988; Akatugba & Wallace, 1999; Tingle & Good, 1990).

Working Memory Capacity

In the 1950s with the increasing number of studies in the field of information processing, the debate about the function and the description of short-term (working) memory showed a major increase (Baddeley, 1986). One view is that short-term and long-term memories are the two components of one big system. Each part is used under certain conditions. An alternative view is that long-term and short-term memories are two distinct systems, which function simultaneously to execute the complex tasks (Kintsch, 1970). Yet another view is that short-term memory, which refers to working memory, is not a single system but a complex set of subsystems (Baddeley, 1976). For example, when a person needs to remember an address or phone number and do other mental tasks at the same time, short-term memory must control and direct the available cognitive resources like the traffic lights that regulates the traffic coming from all directions. (Baddeley, 1976).

Working memory plays en essential role in manipulating information and the performing the complex cognitive tasks such as learning and reasoning (Baddeley, 1986). Research (Miller, 1956; Shiffrin & Nosofsky, 1994) has revealed that the size of working memory is not limited, in other words, working memory has a capacity. This is an important fact that educators should always keep in mind while preparing the materials for their classrooms and laboratories because the research indicates that the

comprehension of the fundamental principles and solving problems in chemistry have potential information overload associated with them (Johnstone & El–Banna, 1986; Johnstone, 1984; Johnstone & El–Banna, 1989).

Johnstone and Kellett (1980) believe that developing a conceptual understanding (knowledge) influences the students' success in solving problems. During the problem solving, students need to recall procedures, facts, rules, and principles from their long-term memory while processing the information in their short-term memory. It is obvious that being fluent and flexible in recalling the information will increase the chance of being successful in solving the problems. The best way to increase the students' competence in recalling the information is to help the students develop a conceptual knowledge, which is identified by an organized knowledge system formed with the chunks of knowledge pieces, which are grouped around the core principles. As students' conceptual understanding increases, they restructure their knowledge system, form new connections among the pieces, and construct larger "chunks" of information. This reduces the information load on working memory and eventually helps the students be more successful in solving problems (Johnstone & Kellett, 1980).

Johnstone and El–Banna (1986) further explain the relationship between working memory capacity and success in chemistry. They also claim that working-memory capacity is a good predictor of student performance in

problem solving in chemistry. Based on their assertion, there are two approaches can be taken. The first one is to present the material in science classrooms in a way that does not demand more than learners' working memory capacities. The other view is that students should be challenged with the tasks demanding above learners' working memory capacities so that the students can operate beyond their capacities. The authors (Johnstone & El–Banna, 1986; Johnstone, 1984; Johnstone & El–Banna, 1989) present data from both secondary and tertiary education and conclude that the results are in general agreement with their hypothesis, but do admit that working memory capacity is not the only factor effecting a students performance.

Furthermore, Opdenacker et al. (1990) investigated the correlation between working memory capacity and problem solving performance, as hypothesized by Johnstone and El–Banna (1986), using two hundred and fifty undergraduate medical students. Again, the DBT and FIT were used to assess the working memory capacity of students. In the discussion of their results, they state that their results do not lead to a straightforward confirmation of Johnstone and El–Banna (1986). They do find, however, a moderate correlation between the size of working memory and problem–solving ability. In the end, they point out that working memory capacity is only one of the factors affecting problem solving ability.

The Interaction of Problem Solving with More Factors

Domain Specific Knowledge

During the examination of the literature, we found that there are more factors such as strategies, domain-specific knowledge, heuristics, and algorithms in addition to other factors, which were previously mentioned in this chapter, affecting students' performance in problem solving. I think before discussing the effects of other factors on problem solving, we should first talk about domain specific knowledge . I believe that students can benefit from other skills such as using algorithms and having heuristics (Wilson, Fernandez, & Hadaway, 2003) only if they have a substantial domain specific knowledge, which is a base of field knowledge – factual "pieces" of knowledge,.

The importance of domain-specific knowledge and skills can be understood better when experts are given problems that are not in their field of expertise. For example, when a biologist is given a physics question about the kinetic theory, it is unlikely she will be able to solve that question although she may use scientific reasoning. The same person, however, may be more successful when she is given a question regarding an everyday event, such as "should city water be chlorinated?" In the first case, the most

important factor is domain-specific knowledge whereas in the second case procedural knowledge is important in addition to basic scientific literacy.

General cognitive skills cannot be replaced by domain-specific knowledge or vice versa. They function in different ways depending on the domain and they complement each other. Cognitive skills, which are like human hands, are necessary to retrieve and manipulate the domain specific knowledge (Perkins & Salomon, 1989).

Researchers interested in artificial intelligence highlight the limitations of general problem solving heuristics and call them as *weak methods* (Perkins & Salomon, 1989). Studies also revealed that there is not significant increase in students' success after teaching Polya's (1945) heuristics to students for mathematical problem solving. Although students seem to understand the heuristics in general, they could not employ them in context bound ways (Perkins & Salomon, 1989). Domain specific knowledge appears more important than general problem solving heuristics.

In the following analogy, we may see better how the specific knowledge is superior over the general cognitive skills. Imagine a well-known cook who is very skillful and works in a beautiful restaurant where he finds the most healthy and fresh ingredients (domain specific knowledge) to cook delicious foods (solving problems). Later, he goes to another country where he cannot find the same ingredients to cook delicious foods although he has all recipes and skills (general cognitive skills) to cook tasty foods. Research on

transfer (Perkins & Salomon, 1989) suggests the same conclusion. Children do not benefit significantly from general and context-independent cognitive strategies outside the specific domains in which they are taught.

Strategies

Strategies used in problem solving directly related to the interaction between the task and the person struggling to solve the problem (Bodner, 1991). This interaction will tell us why experts in Heyworth's study (1991) prefer to use working forward method whereas novices favor means-ends analysis as their common strategies. When experts are asked if they were recognized the problem, they responded as follows (Heyworth, 1999, p.199):

> Yes, immediately! When I look at the question I think *I know how to do it*…Because it is common. We've done it many times before…I know how to do it.

Their answers reminded me the definition of problem given by Hayes (1981) and discussion between Smith and Wood about the differences exercises and problems. According to Hayes (1981), while solving problems, we cannot always see an obvious way of crossing that gap. On the other hand, the solution of exercises does not require so much work because in solving exercises, the way to the solution is clear and people just need to apply a correct algorithm. Thus, in this case, I think experts were not solving a problem; rather they were doing an exercise. Therefore, experts employed

working forward strategy without having difficulty and solved the question rapidly. On the other hand, novices might not be familiar with the problem type. In this case, they could not link the data and the goal and they were not sure what to do and were really solving a problem according to Hayes' definition (Hayes, 1981). Therefore, novices switch strategies to use means-ends analysis strategy instead. Heyworth (1999, p.196) defines commonly used problem solving strategies, working forward and means-ends analysis, as follows:

> These are the "working forwards" and the "means-ends analysis" strategies. With working forwards, the solver begins with the current information in the problem statement and works forwards performing operations to transform it until the goal is reached. Working forwards is associated with previous experience in the type of problem being solved and as Kramers-Pals, Lambrechts and Wolff (1983) have pointed out, is an efficient strategy as it saves time because the problem is familiar and the solver knows the procedure for obtaining the answer.
>
> Means-ends analysis is a form of backward reasoning and involves (a) identifying the goal statement, (b) finding differences between the goal and the current information, (c) finding an operation that will reduce this difference (such as using a formula or equation), (d) attempting to carry out this operation, and if this is not possible then (e) repeating steps (b) to (d) recursively with a series of sub-goals until a solution path is found.

The distinction between strategies used by experts and novices also can be accounted for using the idea of coherent knowledge. Since experts have hierarchically structured knowledge, they know what concepts they need and how to access the concepts to solve problems in an efficient way. On the other hand, novices have ill-structured knowledge, they don't

know/cannot identify what they need or how they can find those pieces to solve problems. Thus, they usually prefer to use the means-ends analysis to solve the problems.

Heuristics and Algorithms

In addition to employing the common strategies in order to solve everyday and scientific problems, people develop a set of unique methods using the available sources of knowledge, conceptual and procedural, and skills. These unique methods are labeled as heuristics. These heuristics can help problem solvers to produce solutions and guide them to get the answer (Wilson, Fernandez, & Hadaway, 2003). On the other hand, algorithms can be thought of as the rules, which are used to do calculations or procedures, which are specific to certain type of exercise or problem (Wilson, Fernandez, & Hadaway, 2003).

The solutions of the problems always demand more than use of a simple algorithm but exercises can be solved successfully when a correct algorithm is followed (Frank & Baker, 1987). A problem first needs to be decoded and transformed into a recognizable form before the type of algorithm is chosen for it. Algorithms can be helpful when the problem solver comes to the stage where he knows what he needs to do (Gendell, 1987). The use of algorithms is essential for exercises as well as problems but it should

not be thought of as a goal in problem solving but a tool, which can help problem solver to reach the correct answer. Unsuccessful students unfortunately do not understand the function of algorithm properly and look for an algorithm first when they encounter a problem before they decide in what direction they need to go.

Conclusion

It is apparent that there are so many factors affecting problem solving process. It is almost impossible to handle all the variables in a single research piece. However, I believe that we should still do our best and design our studies in a way that we might incorporate as many variables as we can in order to reach to more holistic and rational conclusions about the very complicated process of problem solving. Unfortunately, researchers generally prefer to observe the effects of one of the variables on problem solving at a time since it is perceived difficult to study the effects of multiple variables on problem solving at the same time.

Nevertheless, any research aiming to observe effects of one variable on problem solving at a time will not be able to account for covariances and will be limited as a result. A successful way to conduct research on problem solving is to take a combination of knowledge and several cognitive, metacognitive and motivational variables into consideration simultaneously

(Mayer, 1998). Since I considered this as an important fact, I think that the discrepancies between successful and unsuccessful students' problem solving performances is best understood by considering and examining as many variables affecting their problem solving success in chemistry as we can.

CHAPTER III

METHODOLOGY

In this study (involving 17 students in a chemistry course at a public university in northwestern Indiana), I aimed to find out whether there are differences between successful and unsuccessful non-chemistry majors' problem solving performances in stoichiometry and, if the difference exists, discover the sources of those differences. If we want to have a larger fraction of our students solve chemistry problems successfully than is presently the case, we have to understand what distinguishes successful from unsuccessful students.

Finding the differences between successful and unsuccessful students is not an easy task because there are so many variables affecting their performance. Students do not only bring their prior understanding of chemistry concepts to class, they might also bring different cognitive abilities and different assumptions about the nature of chemistry knowledge, what they are to learn, what skills will be required, and what they need to do to succeed.

Research in science and mathematics education has revealed evidence that often students are unsuccessful because their knowledge of science and mathematics is fragmented into unconnected procedural pieces (Pasceralla,

2004; diSessa, 1988; Anderson, 1993). As a result, unsuccessful students have difficulty in applying what they have learned in science and math classes while solving problems in chemistry and other classes. In this study I examined the ability of students to link together pieces of knowledge.

In order to analyze the differences in general academic ability between successful and unsuccessful students, I investigated several cognitive variables. These included developmental level, working memory capacity, logical thinking, and proportional reasoning ability. At the same time, I also examined their understanding of particle nature of matter and the mole concept.

Besides considering the variables listed, I tried to be open-minded to keep my eyes and mind open as much as possible to catch different patterns among subjects' problem solving trials. This strategy has helped me to make a holistic account for the difficulties which students have while solving stoichiometry problems.

Research Questions

In this study, I used three questions as my guide:

(1) To what extent do the difficulties in solving stoichiometry problems stem from poor understanding of pieces (domain-specific knowledge) versus students' inability to link those pieces together (conceptual knowledge)?

(2) What are the differences between successful and unsuccessful students in knowledge, ability, and practice?

(3) What are the roles of cognitive development, formal (proportional) reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in successful and unsuccessful students' problem solving success in stoichiometry?

The Framework of the Selected Topic: Stoichiometry

Stoichiometry is a way of describing the quantitative relationships among elements in compounds and among substances as they undergo chemical changes. In plain English, if you have to calculate just about anything related to moles or other chemical quantities, the calculations will involve stoichiometry. In stoichiometry, the following topics are typically included:

a- Writing Chemical Equations (WEQ)

b- Balancing Chemical Equations (BEQ)

c- Mass Percent (MP)

d- Empirical Formula (EF)

e- Molecular Formula (MF)

f- Percent Yield (PY)

g- Limiting Reagent (LR)

h- The Mole Concept (MC)

i- Stoichiometric Ratio (SR)

The Figure 3.1 below shows a map used as a guideline in stoichiometric calculations by most chemistry students and teachers.

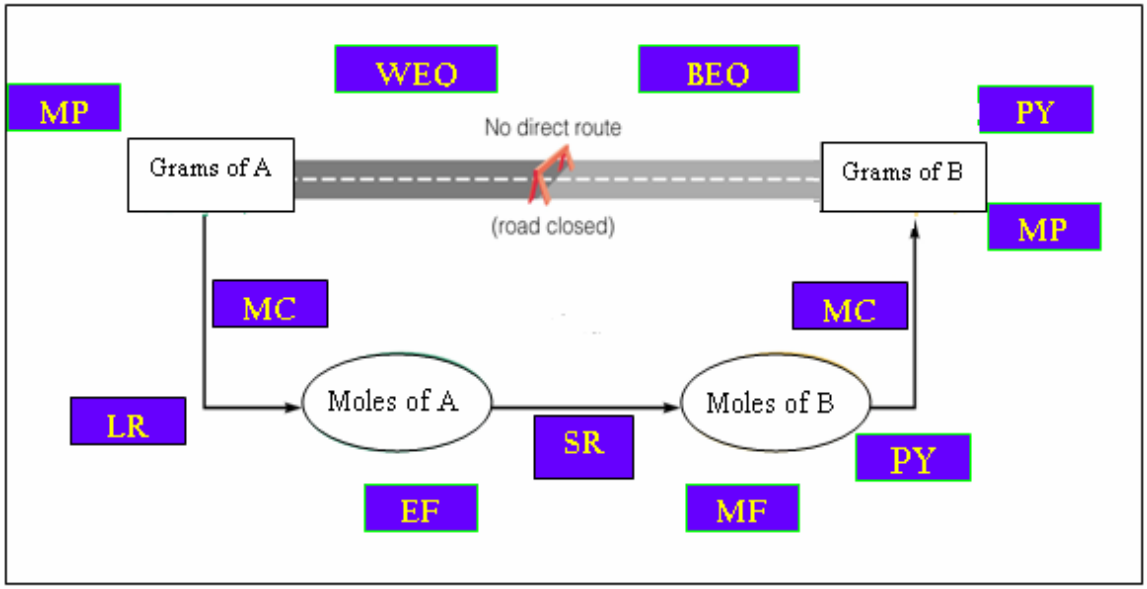


Figure 3.1: The main pieces used in stoichiometry problems and the roadmap used in solving stoichiometry problems

Although all the pieces are not necessary to solve any given stoichiometric problem, these are the pieces needed for solving stoichiometry problems in general. Some types of the stoichiometry problems involve the gases but in this study I didn't include those types of questions because it would have made the study more complicated without qualitatively increasing the value of the study.

The Structure of Stoichiometry Questions Used in the Study

The questions students solved during the study protocols were prepared under two different categories:

(1) The first group of questions were designed to evaluate a small number pieces of stoichiometry at a time. The pieces involved in these simple questions can be seen in Table 3.1.

Table 3.1
Simple Questions (Exercises) Used During the Think-Aloud Protocols

TYPE	E	SUCCESS (%)	AVE. (%)	PIECES INVOLVED	# OF TYPES OF PIECES	AVE.
SIMPLE QUESTIONS (EXERCISES)	E1	65	88	WEQ & BEQ	2	2.3
	E2	89		WEQ & BEQ	2	
	E3	100		WEQ & BEQ	2	
	E4	80		WEQ & BEQ	2	
	E5	97		MP & MC	2	
	E6	76		MC & EF	2	
	E7	89		MP & MC & MF	3	
	E8	78		WEQ & BEQ & PY & MC & SR	5	
	E9	87		WEQ & BEQ & MC & LR & SR	5	
	E10	100		MC	1	
	E11	94		MC	1	
	E12	94		MC	1	
	E13	76		WEQ & BEQ & MC & SR	4	
	E14	94		MR	1	
	E15	94		MR	1	

The more important characteristics of these questions were:

a- These questions were the type very often used by the instructors and textbooks to help the students learn the individual pieces of stoichiometry. Typically, students are familiar with the type of question.

b- These questions typically are of low difficulty. These questions can be thought of as simple exercises.

c- Even though some of these questions involved up to five pieces, the questions did not require students to use more than straightforward algorithmic methods.

Table 3.2
Complex Questions (Problems) Used During the Think-Aloud Protocols

TYPE	P	SUCCESS (%)	AVE. (%)	PIECES INVOLVED	# OF TYPES OF PIECES	AVE.
COMPLICATED QUESTIONS (PROBLEMS)	P1	82	69	MP & MC	2	3.5
	P2	63		LR & PY & SR & MC	4	
	P3	50		WEQ & MC & SR & EF	4	
	P4	72		WEQ & BEQ & MC & SR & MP	5	
	P5	78		WEQ & BEQ & MC & SR	4	
	P6	62		MP & MC & SR	3	
	P7	89		BEQ & MC & SR & PY	4	
	P8	53		MC & SR	2	
	P9	50		WEQ & BEQ & MC & SR & MP	5	
	P10	86		BEQ & MC & SR	3	
	P11	72		MP & MC & EF	3	
	P12	67		MC & SR & PY	3	

(2) The second type of complex questions involved at least two, but often more pieces of stoichiometry. Table 3.2 indicates the pieces involved in complicated questions. Again, for these questions, the number of the pieces was not the most important aspect.

The main distinctive characteristics of these questions were:

a- These questions are not assigned as frequently by instructors and occur in smaller numbers in textbooks. Thus, students are not as familiar with this type of the question.

b- The interaction between the pieces in these questions is usually complicated.

c- For their solutions, simple algorithm and straightforward strategies were not enough. As we shall see, students often struggled to find out what strategy and set of steps they needed to follow to solve these questions successfully. Consistent with these descriptions, these questions could be referred to as true problems.

All questions are reproduced in Appendix H. The first group of the questions is represented by the letter, E and latter ones are represented by the letter, P. For example, E1 is the first question of the simple questions (exercises) and P3 is the third question of the complex questions (true problems). Each student solved 15 simple questions and 12 complex questions during four think-aloud protocols (described below). Each think-aloud session was one-hour long.

The distribution of the questions for each topic (piece) in stoichiometry was as follows: (1) writing and balancing the chemical equations- 4 questions, (2) - mass percent (percent composition)- one question, (3) the mole concept- 3 questions, (4) limiting reagent- one question, (5), percent yield- one question, (6) determination the empirical formula- one question, (7) finding the molecular formula-one question, (8) stoichiometric ratio- one question, (9) mathematical ratio- one question, and (10) complex stoichiometric questions- 12 questions.

I prepared the questions under two different categories to see how students' understanding of individual pieces in stoichiometry influences their performance when they faced difficult problems. I wanted to find out if students' knowledge is compartmentalized and if they can link their knowledge pieces as they deal with complex questions. The sequence of questions that students solved each time was random. Assigning questions randomly was more appropriate for the purpose of this study because I did not want to influence their thinking in any way by giving the questions in a certain sequence.

Subjects

The results of research using the same questions to analyze the problem solving skills and performance of experts and novices is controversial

when experts are chosen from among professors and novices are chosen from among students (Smith & Good, 1984; Heyworth, 1999). The questions used in the research might be true problems to novices and simple exercises to experts. To compare the performance of experts, who are usually faculty or PhD students trained in the field, with that of novice students enrolled in the course the first time, we need to prepare the questions difficult enough to require more than recall for the faculty and yet simple enough to allow the students a chance to obtain the solution (Smith & Good, 1984).

Although this can be done, it is difficult to avoid comparing the performance of experts working on routine exercises with that of students working on novel problems. Therefore, it might be better if we choose experts among successful students and novices among poor students or simply we can compare successful students with unsuccessful ones in the same classroom (Heyworth, 1999).

For the reasons mentioned above, I chose my subjects from two different groups, successful chemistry students and unsuccessful chemistry students who were registered in general chemistry course, CHM 116, in Spring 2006. The chemistry course, CHM 116, is the continuation of CHM 115, which I ran labs for during Fall 2005. Thus, I knew many of the students from the previous semester. I was not involved in anyway, however, with the teaching of CHM 116 in Spring 2006 when this study took place. I believe this made students comfortable during the study because they knew that

they were going to work with someone they had been familiar and yet the results of the study would not affect their grades in CHM 116.

After gaining HSIRB approval, which can be seen in Appendix A, and with the consent of the faculty teaching CHM 116, I informed students about the study, its purpose and design, and invited them to participate. In order to encourage their interest in the research I also highlighted the possible contribution of the study to their and other students' learning of chemistry. I made very clear the point that their participation in the study was voluntary and their decisions and actions would not have any negative impact on them. Moreover, I clearly explained to them that all the information provided would be strictly confidential.

Following the announcements and encouragements, the process of students' selection was started. As we said, our target population was including the students taking the CHM 116. In Spring 2006, there were 42 registered students in this class. We decided to choose 18 students because this number was consistent with the practice in other qualitative research found in the literature review. Considering the amount of time and effort necessary for conducting qualitative study and analysis of qualitative data, the number of subjects was reasonable and practical.

In order to choose the most appropriate subjects for my study among 42 students, I used chemistry achievement test (CAT) including fifteen questions about stoichiometry, which can be seen in Appendix B. I and other

three chemistry professors together chose the questions and formed the CAT. I believe this test was a very good instrument to identify the right students for the study. The high correlation ($r=.84$, $p<0.01$), which can be seen in Table 4.34, between the CAT and results of think-aloud problem solving protocols is also evidence to believe that the CAT was a good instrument for the purpose of our study.

After the CHM 116 volunteers read and signed the consent form, they took the CAT. I carefully graded all the students' tests and ranked them based on their scores. Seven students scored above 70% and six students scored 40% or less. Since I was planning to have 18 students and equal number of successful and unsuccessful students, I increased my lower score from 40% to 47% to have as many unsuccessful students as we had planned. Later, based on my colleagues' experiences I also decided to change my upper score from 70% to 67% to choose more successful students than I had initially planned. Finally, I identified nine of students as my successful students and nine of them as my unsuccessful students based on their scores. However, one of the subjects (S05) quit after the first interview due to scheduling conflicts. I continued with 17 subjects in the study. Table 3.3 shows all the details about subjects such their age, gender, pseudonyms, etc.

Table 3.3
All the Subjects in the Study

SBJ	PSEUDONYM	G	A	MAJOR	YEAR AT COLLEGE	PROFESSION DESIRED
1	Silas	M	19	Engineering	Freshman	Mechanical Engineer
2	Jason	M	28	Biology	Sophomore	Park Naturalist / Environmentalist
3	Brooklyn	F	23	Pre-Pharmacy	Sophomore	Pharmacist
4	Tammy	F	25	Business	Senior	Works for a pharmaceutical company
6	Guillermo	M	21	Engineering	Sophomore	Mechanical Engineer
7	Aubrey	F	18	Biology	Freshman	Dentist or Orthodontist
8	Lady	F	18	Pre-Pharmacy	Freshman	Pharmacist
9	Nanette	F	19	Pre-Veterinary	Freshman	Veterinarian
10	Kristen	F	19	Biology	Freshman	Ecologist
11	Steve	M	20	Engineering	Sophomore	Electrical Engineer
12	Santiago	M	21	Pre-Veterinary	Sophomore	Veterinarian
13	Gwen	F	22	Biology	Sophomore	Environmentalist
14	Bob	M	27	Biology	Sophomore	Physical Therapist
15	Faith	F	25	Pre-Pharmacy	Sophomore	Pharmacist
16	Vanessa	F	45	Biology	Sophomore	Environmentalist
17	Amelia	F	19	Pre-Pharmacy	Freshman	Pharmacist
18	Yang	M	19	Engineering	Freshman	Mechanical Engineer

Since I had believed we could get more insight and information related to problem solving performances using these two extreme groups, I was not interested in those students who had average scores, between 47% and 67%.

The other reason why I used these two groups was directly related to the one of the important goals of the research in education, finding methods and techniques to make students more successful. If we know where unsuccessful students have more difficulty and how and why successful students show a better performance while solving problems, we might be more helpful for poor students.

I contacted the 18 selected subjects and let them know that they were found eligible for this study. These subjects were financially compensated for their time with the amount of $12 payment at the end of each test-taking session and with the amount of $7 payment at the end of each interview. They also received a bonus in the amount of $8 after the fourth interview since they attended all four interviews.

Overall Design and Data Collection Methods

The research used both quantitative and qualitative methods because mixed-method has several advantages. The mixed-method:

(1) checks the reliability of findings through different instruments and facilitates triangulation (Green et al., 1989);

(2) elucidates results from one method with the use of another method (Green et al., 1989). In my case, think-aloud protocols will add information

about the problem solving process and will qualify the scores and statistics; and

(3) makes the study richer and more detailed by exploring specific features of each method (Green et al., 1989). Moreover, studies using mixed-method have shown that integration of these traditions within the same study can be seen as complementary to each other (Caracelli and Greene, 1997).

The tests made up the quantitative part of the research and think-aloud protocols constituted the qualitative part of the research, which mainly helped us to see the interaction between students' organization of knowledge and problem solving performances. Both parts helped us answer our first and main question of the research, "To what extent do the difficulties in solving stoichiometry problems stem from poor understanding of pieces (domain-specific knowledge) versus students' inability to link those pieces together (conceptual knowledge)?".

Several instruments were used to measure different variables:

- Chemistry Achievement Test (CAT) for identifying successful and unsuccessful students (Appendix B),
- Test of Logical Thinking (TOLT) to measure formal (proportional) reasoning abilities of subjects (Appendix C),
- Berlin Particle Concept Inventory (BPCI) to find out subjects understanding of particle nature of matter (Appendix D),

- Mole Concept Achievement Test (MCAT) to see how subjects are particularly successful at using mole concept (Appendix E),
- Longeot Test (LT) to determine subjects cognitive development (Appendix F), and
- Digits Backwards Test (DBT) to detect subjects' working memory capacities (Appendix G).

I made sure that the students understood that their input as subjects to this study was key to its completion. Once all students understood what we wanted from them as subjects and what their rights were, I communicated with each one to find a common day to give the tests. All 17 students had tests in two different days and together because it saved a lot of research time. The first day subjects had the TOLT and BPCI. For both tests, 80 minutes were given to administer. On the second day of meeting with subjects, I gave them other two tests, the LT and MCAT. In the same manner, for these tests, subjects had 80 minutes to complete. At the end of the second day I asked subjects to give me their available times for think-aloud protocols. These think-aloud sessions were scheduled for four different appointments on four different days. After I finished scoring and grading the tests, I started scheduling think-aloud protocols according to subjects' available times. We initiated the think-aloud protocols through the mid-March. The think-aloud protocols continued for about two months.

The chronology of the think-aloud protocols is as follows. On the first day of the think-aloud protocols, I administered the last test, DBT to determine subjects' working memory capacities. This test took about 20 minutes of the first session. In the rest, subjects started to solve problems as they were thinking aloud. The number of questions varied from subject to subject for this first session. Some solved two and some solved three questions. They solved questions coded as P1, P3, and P4. The ones, who solved two problems in the first protocol, stayed longer in the second meeting and solved more questions.

In the second session, subjects attempted to solve twelve questions-E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11, and E12- about the writing and balancing reactions, percent composition, empirical and molecular formula, percent yield, and mole concept. In the third session, subjects, in a similar manner, solved seven stoichiometric questions-P5, P6, P7, P8, E13, E14, and E15. Finally, in the last session, subjects finished think-aloud protocols by solving five more complex stoichiometric questions-P2, P9, P10, P11, and P12- evaluating their problem solving performance in stoichiometry.

Quantitative Test Descriptions

The quantitative data was collected by administering different tests and scoring them. Each test is described below.

The first test subjects took was the Test of Logical Thinking (TOLT) (Tobin & Capie, 1981; Tingle & Good, 1990). The TOLT is a paper and pencil instrument, which evaluates logical thinking. The first two items measure proportional reasoning, the third and fourth items measure the control of variables, the fifth and sixth items measure probabilistic reasoning, the seventh and eighth items measure correlational reasoning, and ninth and tenth items measure combinatorial reasoning. Each of the first eight items consists of two parts, an answer and a rationale for that answer. Both parts must be correct for the students to score on the item. For the items nine and ten, the students must have every possible combination to score a point. Although, in the original version, the test was scored on a scale of ten, I used the scale of 100. Students were allowed 40 minutes to complete the TOLT.

Table 3.4
Types of the Questions in the TOLT

Questions	Types
1-2	Proportional Reasoning
3-4	Control of Variables
5-6	Probabilistic Reasoning
7-8	Correlational Reasoning
9-10	Combinatorial Reasoning

The TOLT has been used with students in several grades from middle school to college. The reliability of this test had ranged from .80 to .85 (Tobin & Capie, 1981). The TOLT had been shown to be a good predictor of chemistry

achievement (Sanchez & Betkouski, 1986). The proportional reasoning items had showed adequate reliability (r=.82) to give idea about students' proportional reasoning ability (Tingle & Good, 1990). Looking at the overall TOLT score, it appeared that students scoring below 60 % had difficulty with chemistry, especially with quantitative aspects.

Second test in the study was the Berlin Particle Concept Inventory (BPCI). The BPCI was developed by Silke Milkelskis-Seifert in Germany and translated into English by a group of researchers at Kansas State University (Cui, Zollman, & Rebello, 2005). The BPCI contained 70 statements, each of which was rated on a four-point Likert Scale from true to false. Respondents also rated themselves as being either certain or uncertain of each answer. A reason for using the Likert Scale was that for most of the questions, the correct answer for a novice may be incorrect for an expert and even the experts may disagree based on their level of expertise. For example, it might be difficult to have consensus on the following statement: "Since particles exist, sooner or later their size and shape will be determined exactly." (Cui, Zollman, & Rebello, 2005). Moreover, Likert Scale questions allowed us to study the vagueness of student choices that might better represent their mental models.

In the BPCI, the questions were categorized into eight categories as suggested by Cui et al. (2005): (1) Existence of particles and their experimental evidence, (2) relationship between characteristics of the

individual particles and characteristics of the object they form, (3) material (air or vacuum) between the particles, (4) density, volume, mass, weight, and their relationship, (5) forces between particles, (6) difference between solid, liquid, and gaseous state, (7) relationship between shape, mass, and volume of the individual particles, (8) relationship between temperature and particle properties. The inter-rater reliability of the categories was 82% (Cui et al., 2005).

As third test, subjects had the Longeot Test (LT) (Sheehan, 1970). The LT, originally published in French, was a paper-and-pencil test designed to measure various aspects of formal thinking. Its twenty –eight items were divided into four parts. The first part contained five items involving the concept of class inclusion. The second part of the test had six items of propositional logic while the third part consisted of nine items designed to measure proportional reasoning. The fourth part of the test consisted of eight combinatorial analysis problems requiring subjects to list all possible combinations of a set of items.

Validity and reliability of the English version of the Longeot test had been studied by earlier investigators (Pandey, Bhattacharya, & Rai, 1993; Sheehan, 1970; Ward et al., 1981). Sheehan's results (1970) indicated that the test was effective in differentiating between concrete and formal thinkers. Ward et al. (1981) found the test to be valid as scores exhibited a significant correlation ($r=.62$, $p<0.01$) with the sum of two Piagetian tasks (balance

beam, flexible rods). They claimed the test to be reliable as the internal consistency ranged from 0.72 to 0.78 over a wide range of class type.

Ward et al. (1981) used the LT in their study to investigate the reliability of the test itself by analyzing the results of the test in the SPSS and they found reliable. Sheehan (1970) found the influence of instruction in science on the group of students, which were determined using the results of LT test. He chose his students from the grade 4 to 9. Smith and Van Egeren (1977) did a very similar study but investigated high school students' success in chemistry classrooms. Like Smith and Van Egeren (1977), Gabel and Sherwood (1979) chose their students among high school students. However, they designed the study in a different way to see if there was any interaction between students' developmental levels and ACS and NSTA chemistry achievement exams. Although they did not run a detailed statistical analysis, the comparing the students' cognitive developments and their ACS scores revealed that the students at formal formal-operational level had better scores. In our study, like in Ward et al.' study (1981), we used the LT to measure the cognitive developments of undergraduates. We differently aimed to find out if there is a correlation between college students' cognitive developments and their success on stoichiometric problem solving.

Fourth test in the study was the Mole Concept Achievement Test (MCAT)). This test was developed by the researchers (Gower et al., 1977; Griffiths, Kass, & Cornish, 1983) to identify students' abilities in the

following skills covering the mole concept and meaning of subscripts in chemical formulas (Yalcinalp, Geban, & Ozkan, 1995, p.1086):

> (1) Apply the definition of mole as it relates to the Avogadro's number of atoms or molecules and to the molar mass of an element or compound, (2) determine the number of atoms of a given kind or molecules... present in given mole quantities of elements or compounds, and vice versa, (3) convert a given mass of a compound or an element (or compound) to the number of moles represented, and vice versa, (4) convert the mass of a compound or an element.. to the number of molecules or atoms of the given type present, and vice versa, (5) determine the mass or the number of moles or the number of atoms of an element in a compound from a given mass or number of moles, or number of atoms of another element that is also present in the same compound.

Content validity of the test items was established by a group of experts in chemistry and science education. The reliability coefficient was estimated to be .88 (Yalcinalp, Geban, & Ozkan, 1995). Previous researchers mostly employed the MCAT to examine the students' understanding of the mole concept but we in this study used this test to find out the influence of the conceptual understanding of the mole concept on students' problem solving performance in stoichiometry.

Fifth and the last test was the Digits Backwards Test (DBT) (Johnstone & El–Banna, 1986; Opdenacker et al., 1990). The DBT consisted of reading to the subjects a set of digits and asking them to say them (or write them down) in reverse order. Thus 3245 would return as 5423. In the DBT, subjects were asked to repeat a steadily increasing arbitrary sequence of digits in reverse order. The quantity of working memory capacity, X, was

defined as an integer corresponding to the maximum number of digits that could be repeated in reverse order without mistakes. Students participating in the test repeated aloud and in reverse order the sequence of digits which was read by the researcher. The value of X was taken to be the maximum number of digits, according to the minimum 50% correct criterion (Opdenacker et al., 1990). Johnstone and El-Banna (1986) and Opdenacker et al. (1990) used the DBT along with several chemistry questions including mole concept , solution, and inorganic chemistry questions. However, we did use just stoichiometry questions excluding gas and solution stoichiometry questions.

Final piece of quantitative data was collected by the solutions generated by the students during the think-aloud protocols. Subjects' problem solving performances were graded and regarded as the dependent variable in the study. The interaction between all variables and students' problem solving achievements were investigated statistically.

Qualitative Think-Aloud Protocol Description

The only source of qualitative data, which was the primary focus of our research, was think-aloud protocols. During the protocols, all subjects were given several problems whose types were explained early in the design section. For the period of these think-aloud protocols, problem solving

sessions, I asked the subjects to think aloud and verbalize their thoughts as much as possible (Nakhleh, and Mitchell, 1993; Heyworth, 1999; Tingle & Good, 1990). I also asked some probing questions similar to those that used in *explicitation* interviews. The *explicitation* interview is one of the most appropriate interview formats to elicit data concerning mental actions (Brodeur et al., 2005). This is a special type of interview that attempts to discover as much as possible the spontaneous thinking of the subjects (Potvin, 2005). This type of interview is based on specific techniques that lead the subject to a descriptive verbalisation of his or her experience. It is through the analysis of the verbalizations describing these traces that the interviewer can understand and acknowledge the existence of certain habits of thought.

One of the most important principles of this type of interview is that the interviewer must never ask questions that begin with the word "why" or questions looking for any type of justification. So the explicitation interview type is looking essentially for descriptions of "what is going on in the head" of the subject, according to the subject, when he explores the situations, instead of looking for justifications or ways to answer for his behavior. An example of frequently asked question during this type of interview would be: "When you said this (a prediction, for instance), what did you say to yourself at that moment?" (Vermersh, 2000) We can then see that the main goal is to obtain *descriptions* instead of *constructions*. Thus, explicitation interview is also a

tool that can free the subject from the need to satisfy the interviewer. As it is often said during these interviews, there are no right or wrong answers, just true ones.

Since subjects were not used to thinking aloud while solving problems, I, at the beginning, explained what the important things are in these type of interviews and what exactly I want from them. During the problem solving sessions, I asked probing questions to clarify their explanations and thoughts and encourage them to talk a lot to find out what is going on in their heads. I recorded their thoughts, answers and solutions using digital voice recorder and digital video cassettes. The audio recordings, later, were transcribed for further analysis. As well, I used the digital visual recording to back up the data and make sure that we understand what students are referring or pointing on the reaction or on the solution when they used the words such as this, that, and they. I really benefited from the visual data since subjects often used those adjectives while thinking aloud. However, I did not shoot subjects' faces; the cameras focused just the papers on which the subjects solved the problems.

The problems for think-aloud protocols were carefully chosen to see if subjects' knowledge is compartmentalized and how the knowledge structures influence their problem solving performance and achievement. The problems usually included more than two pieces and their solutions required more than simple algorithm and retrieving simple facts. The problems included more

pieces in average than those in the exercises because their main function to reveal if the students had difficulty in linking the pieces. In addition to using the number and types of the pieces, the difficulty of the problems was adjusted with respect to the information and knowledge, which students need to remember and know to solve the problems.

CHAPTER IV

RESULTS

Introduction

The research questions guiding the study are:

(1) To what extent do the difficulties in solving stoichiometry problems stem from poor understanding of pieces (domain-specific knowledge) versus students' inability to link those pieces together (conceptual knowledge)? (2) What are the differences between successful and unsuccessful students in knowledge, ability, and practice? (3) What are the roles of cognitive development, proportional reasoning abilities, working memory capacities and conceptual understanding of the particle nature of matter and mole concept in successful and unsuccessful students' problem solving success in stoichiometry?

As will be discussed in detail in the following pages, we have found answers to each of the three research questions. The findings of the first question revealed that although students occasionally make algorithmic mistakes, they in general do well with individual pieces. Rather, the main issue for students who show poor performance is the ability to link the pieces together. The findings of the second question show that there are several

differences between successful and unsuccessful students' strategies, knowledge, and cognitive variables. Finally, results from the third question showed that only three of students' five cognitive variables have statistically significant correlation with their achievement in stoichiometric problem solving.

Before getting into details about findings of the questions, we think it best to first define the "pieces." We think it is essential for the reader to know that what we meant by the "piece(s)" in order to interpret the results better. Below each piece is defined, together with how we judged the students' success with them showing the examples for successful and unsuccessful trials.

Defining the Pieces

We were able to divide the solutions to all stoichiometry problems used in this study using the following pieces:

- Writing Equations (WEQ)
- Balancing Equations (BEQ)
- Mass Percent (MP)
- Percent Yield (PY)
- Empirical Formula (EF)
- Molecular Formula (MF)

- Mole Concept (MC)
- Stoichiometric Ratio (SR)
- Mathematical Ratio (MR)

Each piece is described in turn below.

Writing Chemical Equations (WEQ)

Students were considered successful if they were able to write the equations using the correct symbols of the elements and formulas of compounds from chemical names given in the question. Phase symbols (e.g. *s* for solid, *l* for liquid, *aq* for aqueous) were not required but ion charges were.

Question

Write an equation for the following chemical statement: chunks of sodium react violently with water to form hydrogen gas and sodium hydroxide solution (Silberberg, 2006, p.105).

Example for successful trial

$Na + H_2O \rightarrow NaOH + H_2$

Example for unsuccessful trial

$Na + H_2O \rightarrow NaOH + H$, or

$Na + H_2O \rightarrow NaOH + H^+$

Balancing Chemical Equations (BEQ)

Students were considered successful if they were able to balance chemical equations using the fractions or whole numbers correctly so that the same numbers of atoms of each element were on both sides of the arrow.

Question

Balance the following equation: $C_3H_5N_3O_9 \rightarrow CO_2 + H_2O + N_2 + O_2$ (Silberberg, 2006).

Example for successful trial

$2C_3H_5N_3O_9 \rightarrow 6CO_2 + 5H_2O + 3N_2 + 1/2O_2$

Example for unsuccessful trial

$2C_3H_5N_3O_9 \rightarrow 6CO_2 + 5H_2O + 3N_2 + O_2$

Mass Percent (MP)

Students were considered successful if they were able to calculate the mass of the elements or compounds using the mass percent together with the

total mass or calculate the mass percent of the elements or compounds using the molecular or empirical formulas.

Question-1

What is the mass percent of each element in glucose ($C_6H_{12}O_6$)? Molar masses of the compounds and elements are as follows (Silberberg, 2006, p.93):

$C_6H_{12}O_6$: 180 g/mol C: 12g/mol H: 1g/mol O: 16g/mol

Example for successful trial

$$\%C = \frac{72g}{180g} \times 100 = 40\%$$

$$\%H = \frac{12g}{180g} \times 100 = 7.0\%$$

$$\%O = \frac{96g}{180g} \times 100 = 53\%$$

Example for unsuccessful trial

$$\%H = \frac{12}{24} \times 100 = 50\%$$

$$\%C = \frac{6}{24} \times 100 = 25\%$$

$$\%O = \frac{6}{24} \times 100 = 25\%$$

Question-2

What is the mass of C_2H_6 in a 200g-mixture that is 30% CH_4 and 70% C_2H_6 by mass?

Example for successful trial

$$mC_2H_6 = 200g \times \frac{70}{100} = 140g$$

Example for unsuccessful trial

$$mC_2H_6 = \frac{70}{200} = .35g$$

Percent Yield (PY)

Students were considered successful if they were able to calculate or identify both theoretical and actual yield in the question and use the formula of percent yield, PY = (Actual Yield/Theoretical Yield) x 100, to calculate the percent yield.

Question-1

Calculate the percent yield for the CO_2 whose actual yield and theoretical yield are 2.4g and 3.2g, respectively.

Example for successful trial

$$\%CO_2 = \frac{2.4g}{3.2g} \times 100 = 75\%$$

Example for unsuccessful trial

$$\%CO_2 = \frac{3.2g}{2.4g} \times 100 = 120\%$$

Question-2

When 100.0 kg of silicon oxide (SiO_2) is processed with powdered carbon at high temperature, 51.4 kg of SiC is recovered. What is the actual yield of SiC (Silberberg, 2006, p.114)? (Balanced equation: $SiO_2 + 3C \rightarrow SiC + 2CO$) ($SiO_2$: 60g/mol SiC: 40g/mol)

Example for successful trial

Actual yield of SiC is 51.4 kg.

$$m_{SiC} = 100000gSiO_2 \times \frac{1molSiO_2}{60gSiO_2} \times \frac{1molSiC}{1molSiO_2} \times \frac{40gSiC}{1molSiC} \times \frac{1kg}{1000g} = 66.7kgSiC$$

$$PY = \frac{51.4kg}{66.7kg} \times 100 = 77.0\%$$

Example for unsuccessful trial

$$PY = \frac{51.4kg}{100kg} \times 100 = 51.4\%$$

Empirical Formula (EF)

Students were considered successful if they were able to figure out the empirical formula of the compound using the already given or calculated mole numbers of the elements.

Question

What is the empirical formula of the compound, which consists of .696 mol of H, .1394 mol of Cl, and .2795 mol of C?

Example for successful trial

C: .2795 mol /.1394 mol = 2.005 ≅ 2
H: .696 mol / .1394 mol = 4.992 ≅ 5
Cl: .1394 mol / .1394 mol = 1.000 ≅ 1

C_2H_5Cl

Example for unsuccessful trial

C: .2795 mol
H: .696 mol
Cl: .1394 mol

CH_2Cl_3

Molecular Formula (MF)

Students were considered successful if they were able to distinguish the molecular formula from the empirical formula and figure out the molecular formula using the already given or calculated mole number of the elements or empirical formula and molar mass.

Question

What is the molecular formula of the compound (M=90g/mol), which consists of 6.044 mol of H, 3.001 mol of O, and 3.003 mol of C?

Example for successful trial

$$\left.\begin{array}{l} C: 3.003\ mol \cong 3 \\ H: 6.044 mol \cong 6 \\ O: 3.001 mol \cong 3 \end{array}\right\} \quad C_3H_6O_3 \qquad 3\times12+6\times1+3\times16=90 g/mol$$

Example for unsuccessful trial

$$\left.\begin{array}{l} C: 3.003\ mol / 3.001 mol \cong 1 \\ H: 6.044 mol / 3.001 mol \cong 2 \\ O: 3.001 mol / 3.001 mol \cong 1 \end{array}\right\} \quad CH_2O \text{ (finding the EF instead of MF)}$$

or

$C_2H_4O_2$, or C_2HO_2 (using the ratio incorrectly)

Limiting Reagent (LR)

Students were considered successful if they were able to identify limiting reagent using already given or calculated mole numbers and coefficients of the reactants in the balanced equation.

Question

A fuel mixture used in early days of rocketry is composed of two liquids. Hydrazine (N2H4) and dinitrogen tetraoxide (N2O4), which ignite on contact to form nitrogen gas and water vapor. Which one will be limiting reactant when 3.125 mol of N_2H_4 and 2.174 mol of N_2O_4 are mixed (Silberberg, 2006, p.113)? (Balanced equation: $2N_2H_4 + N_2O_4 \rightarrow 3N_2 + 4H_2O$)

Example for successful trial

$$2N_2H_4 + N_2O_4 \rightarrow 3N_2 + 4H_2O$$

Initial (mol):	3.125	2.174
Used (mol):	-3.125	-1.562 (3.125/2)
Left over (mol):	0 (LR)	.612

Example for unsuccessful trial

$$2N_2H_4 + N_2O_4 \rightarrow 3N_2 + 4H_2O$$

N_2O_4 is the limiting reagent because its number of moles was smaller than that of N_2H_4.

Mole Concept (MC)

Students were considered successful if they were able to find the number of moles using either number of particles or mass of the substance or calculate the mass or number of particles of the substance using the number of moles.

Question-1

Silver (Ag) is used in jewelry and tableware but no longer in U.S. coins. How many grams of Ag are in 0.0342mol of Ag (M=107.9 g/mol) (Silberberg, 2006, p.91)?

Example for successful trial

$$n_{Ag} = \frac{m_{Ag}}{MM_{Ag}} \Rightarrow .0342mol = \frac{m_{Ag}}{107.9g/mol} \Rightarrow m_{Ag} = 3.69g$$ 1st method: formula

$$.0342mol \times \frac{107.9g}{1mol} = 3.69g \text{ Al}$$ 2nd method: factor-label method

Example for unsuccessful trial

$$m_{Ag} = \frac{n_{Ag}}{MM_{Ag}} \Rightarrow m_{Ag} = \frac{.0342mol}{107.9g/mol} \Rightarrow m_{Ag} = 3x10^{-4}g$$ 1st method: formula

$$.0342mol \times \frac{1mol}{107.9g} = 3x10^{-4}g \text{ Al}$$ } 2nd method: factor-label method

Question-2

Iron (Fe), the main component of steel, is the most important metal in industrial society. How many Fe (55.85 g/mol) atoms are in 95.8 grams (Silberberg, 2006, p.91)?

Example for successful trial

$$95.8g \times \frac{1mol}{55.85g} \times \frac{6.02x10^{23}}{1mol} = 10.32x10^{23} = 1.03x10^{24} \text{ Fe atoms}$$

Example for unsuccessful trial

$$95.8g \times \frac{1mol}{55.85g} \times \frac{1atom}{6.02x10^{23}mol} = 2.86x10^{-24} \text{ Fe atoms}$$

Stoichiometric Ratio (SR)

Students were considered successful if they were able to find the ratio among the number of the moles of the elements in the same compound or the ratio among the number of the moles of the substances in the balanced equation.

Question-1

The number of moles of S in the compound of $Al_2(SO_4)_3$ is 2.56 mol. What is the number of moles of Al?

Example for successful trial

$$n_{Al} = 2.56mol \times \frac{2}{3} = 1.71mol$$

Example for unsuccessful trial

$$n_{Al} = 2.56mol \times \frac{3}{2} = 3.84mol$$

Question-2

How many moles of $Al(OH)_3$ are produced when 1.5mol of H_2SO_4 is consumed in the reaction, $3H_2SO_4 + 2Al(OH)_3 \rightarrow Al_2(SO_4)_3 + 6H_2O$?

Example for successful trial

$$n_{Al_2(SO_4)_3} = 1.5mol \times \frac{2}{3} = 1.0mol$$

Example for unsuccessful trial

$$n_{Al_2(SO_4)_3} = 1.5mol \times \frac{3}{2} = 2.3mol$$

Extra Piece-Mathematical Ratio-(MR)

Although the mathematical ratio is not a chemistry domain-specific piece, I still wanted to assess subjects' ability of dealing with mathematical ratios to see if there is any difference between subjects' abilities of dealing with stoichiometric and mathematical ratios.

Students were considered successful if they were able to find the ratio between different numbers considering the units.

Question

A furniture factory needs 31.5ft^2 of fabric to upholster one chair. Its Dutch supplier sends the fabric in bolts of exactly 200m^2. What is the maximum number of chairs that can be upholstered by 3 bolts of fabric (Silberberg, 2006, p.15)? (1 m=3.281 ft)

Example for successful trial

$$(1m)^2 = (3.281\,ft)^2$$
$$1m^2 = 10.764\,ft^2$$
$$31.5\,ft^2 \div 10.764\frac{m^2}{ft^2} = 2.92m^2$$

MR

$$1bolt = 200m^2$$
$$3 \times 200m^2 = 600m^2$$

MR

$$1chair = 2.92m^2$$
$$600m^2 \div 2.92\frac{chair}{m^2} = 205.4 \Rightarrow 205chairs$$

MR

Example for unsuccessful trial

$$1bolt = 200m^2$$
$$3 \times 200m^2 = 600m^2$$

MR

$$1m = 3.281\,ft$$
$$600 \times 3.281\,ft = 1968.6\,ft^2$$

MR-incorrectly done (without considering the units)

$$1968.6\,ft^2 \div 31.5\,ft^2 = 62.5 \Rightarrow 62chairs$$

MR

The Codes for the Analysis of the Knowledge Pieces

Successful (S)

I assigned the code "S" to that piece when the calculation for that piece was done correctly or when the subject remembered a needed piece of information correctly.

Example

Write an equation for the following chemical statement:

Write an equation for the following chemical statement, which describes the destruction of marble statuary by acid rain: aqueous nitric acid reacts with calcium carbonate to form carbon dioxide, water, and aqueous calcium nitrate (Silberberg, 2006, p.105).

Answer :

$$CaCO_3(s) + HNO_3\ (l) \rightarrow Ca(NO_3)_2\ (aq) + CO_2\ (g) + H_2O\ (l)$$

Unsuccessful Did Incorrectly (UDI)

I assigned the code "UDI" to that piece when a subject explicitly did something incorrectly.

Example

Balance the following reaction:

$CaCO_3(s) + HNO_3\ (l) \rightarrow Ca(NO_3)_2\ (aq) + CO_2\ (g) + H_2O\ (l)$ (Silberberg, 2006).

Answer :

$CaCO_3(s) + 2HNO_3\ (l) \rightarrow Ca(NO_3)_2\ (aq) + 3CO_2\ (g) + H_2O\ (l)$

Unsuccessful – Guessed (UG)

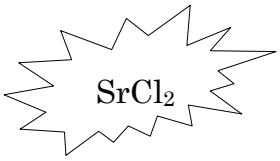
I assigned the code "UG" to that piece when they just guessed without doing necessary calculations or operations. Regardless whether their guess was incorrect or correct, the fact that they simply guessed means they were unsuccessful.

Example

A 0.652-g sample of a pure strontium halide reacts with excess sulfuric acid. The solid strontium sulfate formed is separated, dried, and found to weigh 0.775g. What is the formula of the original halide (Silberberg, 2006, p.132)?

Answer :

$$SrX_2 + H_2SO_4 \rightarrow SrSO_4 + 2HX$$



Subject (S16) wrote the reaction and balanced it. However, she didn't do any other calculation and directly guessed the formula of halide.

Not Required (NR)

I assigned the code "NR" to a piece when the subject solved problem using a different method than the one deemed typical by the investigator and if that step (piece) was not necessary in the subject's method.

Example

Methane and ethane are the two simplest hydrocarbons. What is the mass % of C in a mixture that is 40% methane and 60% ethane by mass (Silberberg, 2006, p.132)?

Answer

Investigator's (Typical) Method

(The typical method assumes that there is 100g of mixture.)

$$mCH_4 = 100g \times .4 = 40g$$

$$mC_2H_6 = 100g \times .6 = 60g$$

$$40g \times \frac{1molCH_4}{16gCH_4} \times \frac{1molC}{1molCH_4} \times \frac{12gC}{1molC} = 30gC$$

$$60g \times \frac{1molC_2H_6}{30gC_2H_6} \times \frac{2molC}{1molC_2H_6} \times \frac{12gC}{1molC} = 48gC$$

% C = 30+ 48 = 78

78% C in mixture

Subject's Method

CH_4: 16g/mol $\Rightarrow$ $\%C = \frac{12}{16} \times .4 = .3$

C_2H_6:30g/mol $\Rightarrow$ $\%C = \frac{24}{30} \times .6 = .48$

% C = .3 + .48 = .78

78% C in mixture

In the subject's method, the subject did not calculate the mole number of C and the mass of C in the mixture. Rather, she first calculated the mass percent of C in each compound and added them to find the mass percent of C in whole mixture. That is why the steps, which were necessary in the typical method, (finding the number of moles of compounds, the number of moles of C in each mixture, and the mass of C in each compound) were not required for this subject's solution.

<u>Could not Do (CD)</u>

I used the code "CD" for the piece when they knew what needed to do but could not do or remember completely (evidence found from the

transcripts). It does not matter if they meaningfully know it or not. They might remember the name of the piece, but still they are aware of it and cannot figure out how to do it. For a CD code to be given, the subject must leave the *piece* blank.

Example

A compound made up of C, H, and Cl contains 55 percent Cl by mass. If 9.00 g of the compound contain 4.19 x 10^{23} H atoms, what is the empirical formula of the compound (Chang, 2007, p.114)?

Answer

$$9.00g \times .550 = 4.95gCl$$

$$4.19 \times 10^{23} Hatoms \times \frac{1molH}{6.02 \times 10^{23} atoms} = 7.00 \times 10^{-1} molH$$

$$7.00 \times 10^{-1} mol \times \frac{1gH}{1molH} = 7.00 \times 10^{-1} g$$

$$mC = 9.00g - (4.95g + .700g) = 3.35g$$

$$nC = \frac{3.35g}{12g/mol} = .083mol$$

Here he made a math error

$$nH = \frac{.7g}{1g/mol} = .7mol$$

$$nCl = \frac{4.95gC}{35.5g/mol} = .140mol$$

He (S02) got this far in the solution and was very close to the final answer but could not find the empirical formula. He knew how to find the empirical formula but could not find it. We got evidence from the subject's transcript:

> S02: I have .083 moles of carbon, now I have moles of all of them, so what I want to do is take the smallest one and make it 1, I think, I have to base it everything off of the smallest one somehow, I'm not sure if empirical formula can have anything but whole numbers I think it has to be whole, I'm not sure how to make whole numbers out of any of this, but what I'm ending up with is .083 mole carbon + 0.7 moles hydrogen + 0.14 moles chlorine.....and like I said if the empirical formula can have anything but whole numbers if it can have fractions it would be easy, *I'd take the smallest one and divide everything by it, I mean I can do that and see what happens...so this would be 1C, .7 over .083 moles, (calculating) so it would 8.43 hydrogen, and this is .14 over .083 (calculating) 1.69 of chlorine,* so there I have a ratio I'm not sure if there is any way in the world to make those all whole numbers I mean there is but I don't know what it is.....I'm thinking now what if I used the biggest one instead but I'm not sure if that matters either....(repeating part of question) empirical formula means the simplest ratio of all atoms or all the constituents. I mean times all these by 2, I could multiply all of them by 3 and I doubt that all of them would hit a whole number at the same time, they might, they might not. I do not know….

Although there was not any empirical formula in his paper, Jason, in his talking, explained his method how he was going to find the EF but could not get an empirical formula. So, we knew that he had known what the empirical formula is and how to get it but for this question he could not get it. .Therefore, he received code CD for this piece, not DD (see below) because he knew that that piece needed to be done and not UDI because he did not report anything.

Did not Know to Do (DD)

I used the code "DD" for the piece when they did not know that they have to consider that specific piece or do the calculation (about the specific piece) and they left this piece blank.

Example

Hydrocarbon mixtures are used as fuels. How many grams of CO_2 (g) are produced by the combustion of 200 g of a mixture that is 25% CH_4 and 75% C_3H_8 by mass (Silberberg, 2006, p.132)?

Answer

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

In order to solve this problem, a problem solver first needs to write and balance the equations. S02 skipped these steps, however, and tried to solve the problem without using them. That is why the code "DD" was assigned for this subject for both pieces, WEQ and BEQ.

$$mCH_4 = 200g \times .25 = 50g$$
$$mC_3H_8 = 200g \times .75 = 150g$$

$$nCH_4 = \frac{50g}{16g/mol} = 3.125mol$$
$$nC_3H_8 = \frac{150g}{44g/mol} = 3.109mol$$

He just found the number of moles of the compounds and tried to use molecular structures to find the mass of CO_2. Naturally, however, he could not naturally finish the solution.

Did Something Else (DSE)

I assigned the code "DSE" to a piece when the subject did not do a calculation about that specific piece and did something else incorrectly or correctly instead. For DSE to apply all of the following must be true:

- The piece is required (cannot use "NR")
- The piece was not left blank (cannot use "DD" or "CD")
- Something altogether different was attempted instead of the piece (cannot use "UDI" or "S").

Example

A chemical engineer studied the reaction:

$$N_2O_4\ (l) + 2N_2H_4\ (l) \rightarrow 3N_2\ (g) + 4\ H_2O\ (g)$$

The chemical engineer measured a less-than-expected yield of N_2 and discovered that the following side reaction occurs:

$$N_2O_4\ (l) + 2N_2H_4\ (l) \rightarrow 6NO\ (g) + 2\ H_2O\ (g)$$

In one experiment, 10.0 g of NO formed when 100.0 g of each reactant was used. What is the highest percent yield of N_2 that can be expected (Silberberg, 2006, p.131?

Answer

In the solution of this question, in order to find the actual mass of N_2, subjects needed to find the actual mass of N_2O_4, its number of moles (MC), the number of moles of N_2 (SR), and the mass of N_2 (MC), respectively. The last step, as you see, is related to the piece of "MC" but some subjects (S01, S04, S06, S13, and S14) just subtracted 10 from the theoretical yield of N_2, which was not related to the piece of "MC" and any other piece. That is why; I assigned the code "DSE".

The reason I did not assign the code "NR" instead of the code "DSE" for this case and in similar cases is lying behind the subjects' solutions for that question. When I investigated their solutions it appeared that the piece to which I assigned the code "DSE" was necessary for their solutions. Therefore, I could not use the code "NR".

The other question might come to our minds "why did not I use the code "DD" instead of the code "DSE"?" The code "DSE" is different from the code "DD" in a way that the code "DD" was assigned only when the subject did not do anything for that piece. However, in the cases where I assigned the

code “DSE” there was always an answer, a calculation or the information. It was the original reason to generate a new code “DSE” to differentiate between the cases where an answer was provided but it was not relevant to any of our pieces (DSE) and the cases where the subject did not put anything for that piece (DD). This also explains why I did not use either UDI or S as the code instead of the code “DSE”. The presented work was not relevant to one of our pieces. For example, subtracting 10 from the theoretical mass is just mathematical calculation, which is not relevant to either “MC” or any other piece. Therefore, I did not put the codes “UDI” or “S” because I was not interested in that calculation at all. To be clear: putting “UDI” would falsely indicate that the subject attempted the piece and made a mistake. With “DSE” the subject does not attempt the piece at all (even though they don’t leave it blank). It does not matter if that part was done correctly or incorrectly. Although I was not interested in math while analyzing the knowledge pieces but, of course, I kept the data regarding the math errors that subjects did throughout the think-aloud problem solving protocols.

Unsuccessful Received Hint (URH)

I used the code “URH” for that piece when they received the hint regarding the one of the main pieces and they were able to use the hint to find a correct answer for the piece.

Example

Write a balanced equation for each chemical statement:

The destruction of marble statuary by acid rain: aqueous nitric acid reacts with calcium carbonate to form carbon dioxide, water, and aqueous calcium nitrate (Silberberg, 2006, p.105).

Answer

$$CaCO_3(s) + 2HNO_3\ (l) \rightarrow Ca(NO_3)_2\ (aq) + CO_2\ (g) + H_2O\ (l)$$

Subjects (except S11, S14, and S18) received the hint, the formula of nitric acid. Since, the writing the equation is the one of the main pieces and hint was provided about that piece, I assigned the code "URH" for the subjects' that piece. This code is used if the final answer was correct. If the answer was incorrect or the subjects did not do any thing, I used appropriate coding, "UDI" or "DD".

Reliability of Codes

Because the assignment of the above codes is a key piece to our data, we thought it imperative that we statistically check that we were applying the codes consistently. The most prevalent reliability tests are the split-half (Cronbach's alpha) and inter-rater (Cohen's kappa coefficient) reliability tests

(Green & Salkind, 2003; Love et al., 1996). Since we as two researchers are dealing with the same data we decided to go with inter-rater reliability method and calculated Cohen's kappa coefficient.

For the purpose of finding Cohen's kappa coefficient, I and Dr. Fynewever first separately analyzed all 17 students' solutions for six questions, which were chosen randomly and included a total of 17 pieces. This meant that we investigated and coded 289 (17x17) pieces in total. After coding all the pieces separately, we grouped all the codes under three groups based on their meanings and their functions in the calculations of the success rates:

- *Group I* - Successful Codes: S
- *Group II* - Neutral Codes: NR, DD, and DSE
- *Group III* – Unsuccessful Codes: UDI, UG, URH, and CD

Following the coding and grouping, we ran the inter-reliability test and found Cohen's kappa coefficient to be $\kappa = 0.82$, which was showing the high reliability of the codes we used in the study.

Answering the First Research Question

To answer the first research question (pieces vs. linking or domain-specific knowledge vs. conceptual knowledge), it is fruitful to consider the typical sort of mistakes that students make on each piece type. Some pieces

are more difficult for students than others – why is that? What is it about the pieces themselves that can be difficult? We will consider each piece in turn below.

To summarize the data for each piece we will calculate the Attempt Success Rate (ASR). ASR is defined as:

$$ASR = \frac{S}{S + UDI + URH + CD + UG} \times 100\%,$$

where the capital letters given in the formula represent the total number of student attempts which received the corresponding codes. Note that this success rate is calculated based only on *attempts*, and as such it excludes those instances where the students were neither unsuccessful nor successful because they simply did not do a certain piece (DD, DSE, NR). We calculate the *ASR* both for individual subjects and as an average over all subjects to determine the general success level with each piece type.

Investigating the Pieces Involved in the Stoichiometry Problems

Writing Chemical Equations (WEQ)

What is WEQ and Why is It Important. A chemical equation is the shorthand that scientists use to describe a chemical reaction. For example:

$$AgNO_3(aq) + NaCl(aq) \rightarrow AgCl\ (s) + NaNO_3(aq)$$

In this equation, $AgNO_3$ is mixed with NaCl. The equation shows that the reactants ($AgNO_3$ and NaCl) react through some process (→) to form the products (AgCl and $NaNO_3$). Since they undergo a chemical reaction, they are changed fundamentally.

Writing a chemical equation is the first and one of the most important steps in solving all types of chemistry problems including stoichiometry problems. It does not matter if you are taking general chemistry, physical chemistry or organic chemistry; you have to deal with chemical equations to some extent. Instructors often expect the students in their classes to be good at and confident with this fundamental step.

On the other hand, as we will see, writing a chemical equation successfully often depends on the degree to which a student has rotely memorized element and compound names and rules related to naming. This rote memorization skill is a low-level skill, and a lack of this sort of knowledge can easily be compensated for with access to appropriate references. For this reason, although we did probe the subjects' ability to recall and use their rote memory, we also regularly provided hints when it was clear that a subject was stuck.

Overall Performance on the WEQ. Table 4.1 shows the details about all students' success rates and problem areas in writing chemical equations. There were four questions, as can be seen in Appendix H, which were

exclusively designed to measure the students' performance in writing chemical equations.

Table 4.1
Subjects' Performance with the Writing the Chemical Equations Piece

SBJ	WEQ											
	45%						88% (After Hint-AH)					
	NR	CD	UDI	DD	DSE	URH	UG	S	S(AH*)	T	%	% (AH)
	0	0	21	7	0	78	0	81	159	180		
01	0	0	0	0	0	3	0	8	11	11	73%	100%
02	0	0	1	2	0	3	0	5	8	9	56%	89%
03	0	0	1	0	0	4	0	6	10	11	55%	91%
04	0	0	2	1	0	4	0	4	8	10	40%	80%
06	0	0	2	0	0	5	0	4	9	11	36%	82%
07	0	0	0	0	0	5	0	6	11	11	55%	100%
08	0	0	2	1	0	5	0	3	8	10	30%	80%
09	0	0	1	0	0	6	0	4	10	11	36%	91%
10	0	0	0	0	0	6	0	5	11	11	45%	100%
11	0	0	1	0	0	5	0	5	10	11	45%	91%
12	0	0	0	0	0	4	0	7	11	11	64%	100%
13	0	0	3	0	0	6	0	2	8	11	18%	73%
14	0	0	1	0	0	3	0	7	10	11	64%	91%
15	0	0	2	0	0	4	0	5	9	11	45%	82%
16	0	0	3	2	0	4	0	2	6	9	22%	67%
17	0	0	2	1	0	4	0	4	8	10	40%	80%
18	0	0	0	0	0	7	0	4	11	11	36%	100%

Additionally, there were several more complex questions whose solutions required the problem solver to write a chemical equation. The average number of chemical equations needed was ten, but this number varied with the method each student followed for solving the problems. The effects of

hints are revealed in Table 4.1, which shows that student success dramatically improved when they were given hints. As illustrated in Table 4.2, most hints were about chemical nomenclature, atomic symbols, or ion charges.

Table 4.2
The Types of the Hints Provided for Exercise # 2

SBJ	HINTS
01	Formula of Nitric Acid
02	
03	Formula of Nitric Acid
04	*Formula of Nitric Acid *Formula of Carbonate ion
06	Formula of Nitric Acid
07	*Formula of Nitric Acid *Formula of Carbonate ion
08	Formula of Nitric Acid
09	*Formula of Nitric Acid *Formula of Carbonate ion
10	Formula of Nitric Acid
11	*Charge of Ca *Charge of Carbonate
12	*Formula of Nitric Acid *Formula of Carbonate ion *Charge of Ca
13	*Formula of Nitric Acid *Formula of Carbonate ion *Charge of Ca
14	
15	*Formula of Nitric Acid *Formula of Carbonate ion *Charge of Ca
16	*Formula of Nitric Acid *Formula of Carbonate and Nitrate ion
17	*Formula of Nitric Acid *Formula of Carbonate and Nitrate ion
18	Charge of Carbonate

I purposefully provided the hints piece by piece in order to discover more details about the types and sources of difficulties the students had. For example, in Exercise 2, out of seventeen students, just two students wrote the chemical equation correctly without getting any hint. All remembered the symbol of calcium but five of them needed to know the charge of calcium, ten of them needed to know the formula of carbonate, and just two of them

needed to know the formula of nitrate. After giving the charge of calcium and formulas of carbonate and nitrate poly atomic ions, I let them to find the chemical formulas of compounds by themselves rather than giving the whole formulas of the compounds as the hints. Using this technique, I could determine if the students knew how to write the chemical formulas of ionic compounds using the charges. Ten of them appeared to have significant difficulty writing the formulas using the charges, but eventually enough hints were given so that all subjects got the formulas right.

Typical Difficulties and Mistakes with the WEQ. In the following paragraphs I will discuss in detail some typical types of difficulties that students have in writing chemical equations. These include:

- Difficulty writing formulae for compounds in which an element is implicit in the compound name.
- Difficulty with questions that are worded in an unusual way.
- Difficulty naming compounds containing elements that possess a variety of possible oxidation states.
- Difficulty with different naming conventions for ionic and covalent compounds.
- Difficulty writing combustion reactions where the presence of oxygen is only implied.

Difficulty in Writing the Formulae of the Compounds with Special Names. Students had more difficulty with the questions in which *the presence of elements was implicit*. For example, in Exercise 2 we used the nitric acid instead of hydrogen nitrate as the name of the acid. This made it more difficult for students to remember the formula of acid. Among seventeen students, just three of them remembered the formula of nitric acid correctly. Although we did not use the hydrogen nitrate in other questions to make sure if the problem was specific to the nitric acid or general, we observed that in other questions, where the names of the elements or the polyatomic ions were explicitly stated, the students did not have this much difficulty with remembering the symbols partially or totally correctly. Therefore, we concluded that when the special names of the compounds were used, the students had more difficulty in writing the chemical equations.

Effect of Wording of the Questions. Students especially struggle when the question is *worded in an unusual way*. For example, the students were confused when trying to write a chemical equation in Exercise 3 for the reaction between phosphorous trichloride and hydrogen fluoride. Exercise 3 was worded as follows: *Halogen compounds exchanging bonding partners: phosphorus trifluoride is prepared by the reaction of phosphorous trichloride and hydrogen fluoride; hydrogen chloride is the other product. The reaction involves gases only. Write a chemical equation for the reaction.* The question was comparatively difficult for the students because it mentions the product

first and then the reactants – this is opposite to the typical order and made the question more difficult.

Difficulty with the Elements Having Multiple Oxidation States. Students also had difficulties with the *writing formulas of the compounds involving the elements that naturally have a variety of oxidation states* such as transition metals: e.g. copper, iron, and manganese. In Exercise 13, students were required to write a chemical equation that involved copper (I) sulfide and copper (I) oxide. Seven of the students did not remember the meaning of the (I) in the given name of copper (I) sulfide and copper (I) oxide. Therefore, they could not write the formulas for those compounds and, naturally, could not complete the chemical equation. Even if some students got the charge of copper correctly, their reasoning was erroneous. When I asked the Jason (S02) the meaning of the (I) in the name of copper (I) sulfide, he said:

> S02: Well it says copper 1 that's the new system of naming, which means there's a charge of 1 on the copper
> I: What do you mean a new system of naming?
> S02: Well the old system...say it was...we'll just say carbon dioxide, in the new system it would be carbon (II) oxide or something like that so.

Difficulties Related to the Naming of Ionic and Covalent Compounds. It also appeared that students had difficulties stemming from not understanding the different naming systems for ionic compounds and covalent compounds. I purposefully spent more time on this difficulty

compared to other difficulties because not only the students in the study but also my own students have often struggled with the difference between the ionic and covalent compounds. Therefore, I dug into this issue more than other issues related to the WEQ piece to find the real source of the difficulty.

While analyzing students' performance of WEQ in Question 13 I first made sure that students knew that the (I) represents the charge of copper, then I asked two questions. The first, I asked why we take the charges of oxygen and copper into consideration while writing the formula of copper (I) oxide and not in writing the formula of SO_2 and, as a second question, I asked why we use the "di" instead of the "two" as the number of oxygen in the formula of sulfur dioxide (SO_2) but not in the formula of copper oxide (Cu_2O). Most students could not account for the difference between two different methods we use to name the ionic and covalent compounds.

Because of the complexity of this difficulty, I will illustrate it by describing the solutions of four students: Jason, Tammy, Nannette, and Bob. Jason, as it turns out, had a partial understanding of the two systems, but needed hints to put the pieces together. I asked Jason how the two compounds are different from each other after he had written the formulas of SO_2 and Cu_2O correctly. Interestingly, he attempted to explain why "sulfur dioxide" is SO_2 using the ionic system of naming (SO_2 is a covalent compound):

S02: Well looking from this one there's a crisscross method for the

> charge so if this has a 2 down here that would make the charge on sulfur 2 but that would make the charge on the oxygen 1 which wouldn't make a lot of sense to me, oh well oxygen in it's natural state is diatomic so if I split this in ½ it would be 1. I still think sulfur is going to be...

After a hint, Jason realized that the compounds fall into two different categories and he correctly sorted the two compounds.

> I: If I tell that your formulas are correct but we are interested in the reasoning behind your methods you used in naming both compounds. Can you explain the difference between two compounds?
> S02: That sounds to me like 1 is an ionic compound and 1 is covalent compound
> I: Which one might be ionic compound and which one might be a covalent one?
> S02: I'm going to say that for sure that copper oxide is ionic
> I: How do you know that it's ionic?
> S02: Technically it's the change in electronegativity, the difference in electronegativities. But a really quick and short way is that they're on opposite sides of the periodic table. Maybe not completely opposite but they are close enough.
> I: How about sulfur and oxygen?
> S02: those would be very close to each other on the periodic table
> I: You mean they are in the same group?
> S02: Yeah ok, so yeah those are covalent.
> I: So, what does that mean?
> S02: So, then funny things happen with covalent, you can't like you said you can't use the crisscross for covalent compounds.

In contrast with Jason, Tammy showed *no* evidence of knowing that covalent and ionic compounds use different systems of naming. Tammy (S04) tried to explain the difference between compounds using the terms, anions and cations. She also could not give the real reason for the difference between the compounds and did not talk about how bonds between the elements in the

compounds are different. Since the things she explained did not make sense to her a lot, she thought that she maybe had not learned this subject yet.

> S04: oh because (pointing the Cu_2O) one (Cu) is a cation and the other one (O) is an anion so but these (pointing S and O) are both anions I think they are negative or is that a cation I think the cations are positive and the anions are negative these are both negative so they're both anions.
> I: so that is why you think we do not use charge over there (pointing SO_2)?
> S04: I have no idea why we do not use the charge over there…you cannot put a two and a two because they would cross out…
> I: ok…
> S04: I do not really know…maybe we have not gone over that yet…or that one at least…

Nanette (S09) clearly knew about how common ionic charges play a role in determining ionic chemical formulae but she unfortunately tried to "map" this knowledge to explain the formula of the covalent compound. She was surprised when she learned that the charge of the elements are not used in writing covalent compounds while they are used in writing ionic compounds. Nanette appeared to be hearing about this difference for the first time. It appeared that she had never thought about the difference between covalent and ionic compounds or she could not make the connection between her theoretical knowledge regarding the ionic and covalent compounds and the compounds given in that question. As a result, Nanette brought an explanation using a similar logic that Tammy used. She said that "well, they (sulfur and oxygen) are both negative and if we use charges it wouldn't

balance anyway" and she could not give any further information regarding the correct reason for not using the charges in covalent compounds.

Finally, Bob (S14), like Jason, had a partial understanding of the different naming systems for ionic and covalent compounds. He at first was not sure if he knew the answer when I asked him to explain the difference between the compounds, Cu_2O and SO_2. However, later, with hints provided by my questions, he remembered the difference between the two compounds and put all the pieces together:

> S14: The copper is given as the charge is 1 because it is copper 1 oxide, so oxygen is a minus 2 almost all the time, so I just put the two coppers with that, the sulfur dioxide, going from copper sulfide, I have 2 coppers for 1 sulfur over here, I, SO2...
> I: Hmm...
> S14: Oxygen has been reduced in the...so those are each minus 1, I think, I don't...
> I: You think the oxidation number has changed.
> S14: Possibly.
> I: Okay, in terms of the elements, how copper is different from oxygen?
> S14: Copper is...Copper is a metal and oxygen is a gas, it is a nonmetal.
> I: Okay, how about the sulfur and oxygen?
> S14: Oxygen is a gas nonmetal and sulfur is a solid nonmetal.
> I: So, they both are nonmetal?
> S14: Yes.
> I: Does that remind you something?
> S14: I'd say it is an anion.
> I: Okay, so what type of compound is this? How they are different?
> S14: This is an ionic compound and this is a covalent bonded compound.
> I: So does that explain why we do not use the charge here (pointing SO_2)?
> S14: Because it is not based solely on charge, it is based on the formation of bonds, but with ionic compounds, it is more...it has to do with the charge of this versus the charge of that.

Bob's and other students' explanations and solutions again revealed that students did not have a good understanding of the differences among the elements or could not remember those differences easily when needed. Moreover, their understanding of the different types of bonding and their properties except that of a few students was not very promising. As a result, they were failing in recognizing the types of the compounds and writing the proper formulae.

Difficulty with Writing Equations for Combustion Reactions and the Situations Where the Multiple Equations Needed. Problem 9 posed two unique difficulties for many students. The students had to recognize that two reactions were needed and that *oxygen is always needed for combustion*. Problem 9 stated: "An ore containing V_3S_4 and V_5S_4 is roasted in air, releasing all the sulfur as sulfur dioxide gas (SO_2), leaving behind metallic vanadium (V)." The question is also worded in an unusual way in that the students are required to write two separate equations:

$$V_3S_4 + 4O_2 \rightarrow 3V + 4SO_2$$

$$V_5S_4 + 4O_2 \rightarrow 5V + 4SO_2$$

However, sixteen of them wrote a single reaction such as, $V_3S_4 + V_5S_4 + 8O_2 \rightarrow 8V + 8SO_2$. Then, some of them tried to solve the problem as if it was a limiting reagent problem before I provided the hint about the equation.

Summary of the WEQ. From the data I collected I can say that students in general were very poor at writing chemical equations. Their

difficulties stem from inadequate *memorization* of chemical symbols, formulas, and charges; and poor knowledge of rules for naming different types of compounds. At this point, instructors should decide to what extent they want their students to engage in the rote memorization necessary to do well on these tasks. If instructors want their students to remember all the chemical symbols and formulas, then instructors should develop new techniques to make the students' task easier to memorize them. If the instructors do not think that remembering the chemical symbols, formulas or charges is necessary, then they should provide the written equations in the questions or provide reference materials to make writing equations achievable. Since we believe that knowing or remembering the symbols of the elements or compounds was low-level tasks in Bloom's taxonomy, providing appropriate reference materials will not significantly affect the measurement of students' higher level thinking abilities and success with stoichiometry problems. Therefore, it is our opinion that teachers should not really demand the memorization of the symbols, formulas, and rules for naming from the students.

In this study we did examine how much students remember about the symbols of the elements and the compounds, but we did not hesitate to provide the hints about the equations where a written equation was necessary for going further in the solution. This enabled us to see how these

students were doing with the other pieces such as balancing equations, finding limiting reagent, calculating mass percent, etc.

Balancing Chemical Equations (BEQ)

What the BEQ is and Why It is Important. Like writing chemical equations, balancing the chemical equations is a very fundamental step in almost every type of chemistry problem. Until the equations are properly balanced, we cannot use the coefficients that represent the relative number of molecules of each compound. We know from the Law of Conservation of Mass (which states that matter can neither be created nor destroyed) that this simply cannot occur. We have to make sure that the number of atoms of each particular element in the reactants equals the number of atoms of that same element in the products.

Balancing a chemical equation is essentially done by trial and error. There are many different ways and systems for doing this, but in all methods, it is important to know how to count the number of atoms in an equation. Developing a general strategy can be difficult, but here is one way of approaching a problem like this. Let us consider the following equation:

$$Al + H_2SO_4 \rightarrow Al_2(SO_4)_3 + H_2$$

i) Count the number of each atom on the reactant and on the product side.
ii) Determine an atom to balance first.

$$2Al + H_2SO_4 \rightarrow Al_2(SO_4)_3 + H_2$$

iii) Choose another atom to balance.

$$2Al + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 + H_2$$

iv) Balance the last atom. Now, we're done, and the balanced equation is:

$$2Al + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 + 3H_2$$

Now this balanced equation can be used as a part of the solution. Since the rest of the solution depends on the success of this step, it has to be done correctly.

Table 4.3
Subjects' Performance with the Balancing the Equations Piece

SBJ	BEQ									
	90%									
	NR	CD	UDI	DD	DSE	URH	UG	S	T	%
	16	0	17	3	0	0	0	151	168	
01	1	0	0	0	0	0	0	10	10	100%
02	1	0	0	1	0	0	0	9	9	100%
03	1	0	0	0	0	0	0	10	10	100%
04	1	0	2	0	0	0	0	8	10	80%
06	1	0	2	0	0	0	0	8	10	80%
07	1	0	1	0	0	0	0	9	10	90%
08	1	0	0	1	0	0	0	9	9	100%
09	1	0	0	0	0	0	0	10	10	100%
10	1	0	0	0	0	0	0	10	10	100%
11	1	0	0	0	0	0	0	10	10	100%
12	1	0	0	0	0	0	0	10	10	100%
13	1	0	2	0	0	0	0	8	10	80%
14	1	0	0	0	0	0	0	10	10	100%
15	1	0	0	0	0	0	0	10	10	100%
16	1	0	4	1	0	0	0	5	9	56%
17	1	0	4	0	0	0	0	6	10	60%
18	0	0	2	0	0	0	0	9	11	82%

Overall Performance on the BEQ. Table 4.3 illustrates both the success of all students and each student's performance. Ten of the students balanced all the chemical equations without any mistake while other students did, on average, only two out of ten questions incorrectly. Only did Vanessa (S16) and Amelia (S17) balanced four chemical equations incorrectly and this lowered the success rate of the whole group.

Typical Difficulties and Mistakes with the BEQ. In the following paragraphs I will discuss in detail some typical difficulties that students have in balancing chemical equations. These include:

- Mistakes due to lack of attention to detail, i.e. carelessness.
- Confusion when dealing with fractional coefficients.

Careless Mistakes. The students' solutions and transcripts revealed that the most common mistakes in balancing equations were *due to carelessness.* Although students usually balanced the equations correctly, they sometimes neglected to check if the equation was balanced or forgot to count each atom. For example, Tammy (S04), Yang (S18), and Guillermo (S06) presented the following chemical equation as a balanced equation but it was not actually balanced:

$$2C_3H_5N_3O_9 \rightarrow 6CO_2 + 5H_2O + O_2 + 3N_2$$

They either did not check at all or checked poorly and did not realize that it was not balanced.

Using Fractions and Difficulty with Connecting Symbolic Representation to the Micro World. Students revealed that they were *confused about when fractions were typically used* and when they were not used as coefficients. When asked the students their opinions about the use of fractions, I received several different interpretations. There were some students believed that the fraction can be used as a coefficient for any substance, some believed that it cannot be used at all, and some others were unsure when fractions can be used as coefficients and when cannot be. All groups either could not account for their beliefs well or brought incorrect reasoning for their preferences.

Like Santiago (S12) and Bob (S14), Gwen (S13) said, "yes, we can" use fractions at first, but also said that she was not sure if the fractions can really be used as coefficients for any substance:

> S13: Yes, we can… From what I remember from this year I believe it is possible.

She then expressed her confusion about her preference:

> S13: I think we started that this year and it really freaked me out because I am so used to having whole numbers…

On the other hand, Guillermo (S06), Aubrey (S07), and Jason (S02) said that it is all right to use the fractions as coefficients. Jason added that he prefers using the whole numbers because they are easier to deal with:

> S02: I think you can as far as balancing; it's probably better to do that with an element. Because that really throws whatever it's with off, if you just do it with a single element it's much easier.

> I: The thing I wonder if you think that we can use the fractions for any substance normally.
> S02: I would think you could. If nothing else you can just multiply everything by 2 and just get whole number. I really hate doing the halves, but I think I might have to though...

When I asked Silas (S01) if he can use the fractions as coefficients for any substance in the equation, $Cu_2S + 3/2\ O_2 \rightarrow Cu_2O + SO_2$, he also told that fractions can be used for any substance. He added, however, that we should be careful while using the fractions because putting a fraction does not mean that we're dividing the atoms:

> S01: Yeah, you could do that...it is not quite convenient to work with if you are just working with molar ratios you could… it is just a lot easier to work with whole numbers and often with the calculations, it is just convenient to work with whole numbers.
> I: So can you divide all the coefficients by the in the equation?
> S01: yeah you could cut them in half if you wanted too. As long as you were just doing things as far as mole ratios... You just have to make sure...you are not thinking like if I had a one point five atoms of oxygen you could not think of it like that or I do not have one point five of copper sulfide...you have to think oh I have one point five moles of oxygen for every one mole of every one mole of copper sulfide that I will have...

In this way, Silas revealed that he was sure that he could not have a half atom.

After the analysis of students' opinions about the use of fractions, I had a better understanding of the mistakes they did regarding the use of fractions. It occurred to me that some students could not connect the micro world to the symbolic representation or vice versa. They treat them separately. For example, when I asked them if it is possible to have a half

atom, they immediately said that "no way" but at the same time, they did not hesitate to put ½ in front of the Na atom as a fraction when it was necessary. We know that as long as the ratio among the elements and compounds in the equations was taken care of, using the fractions or whole numbers will not make any difference in solving the stoichiometric problems. For example, there is no difference in terms of solving the problem algorithmically between the following two methods in balancing the equation for the reaction between the Na and H_2O:

$$2Na + 2H_2O \rightarrow 2NaOH + H_2 \quad (1)$$

$$\tfrac{1}{2}\,Na + \tfrac{1}{2}\,H_2O \rightarrow \tfrac{1}{2}\,NaOH + \tfrac{1}{4}\,H_2 \quad (2)$$

Either equation can be used. It does not make any difference in terms of solving the algorithmic problem solvers. But we know that science educators want their students to not only be successful algorithmic problem solvers want to reinforce correct conceptual understanding. For this reason many would not prefer the second equation because it could give the false conception that atoms can be split. Therefore, this is an instance where I believe that we need to help students see the connections between the micro world and symbolic representations.

Mass Percent (MP)

What the MP is and How it is Used. Another common piece encountered in solving stoichiometric problems is mass percent, in other words, percent composition. There are two types of percent composition problems-- problems in which you are given the formula (or the weight of each part) and are asked to calculate the percentage of each element and problems in which you are given the percentages and asked to calculate the mass of each element (compound) in a compound or mixture.

Overall Performance on the MP. In general, students were successful with the mass-percent piece (87 %). Out of 113 MP pieces, 98 of them were done correctly. The numbers of CD and UDI show that the MP piece could not be done two times and was done incorrectly 13 times, respectively. Out of 17 students, 8 students got a success rate of 100% and just four students got a success rate less than 80%. These figures indicated that students were in general good with the MP piece but there were still some commonly made mistakes.

Typical Difficulties and Mistakes with the MP. Typical mistakes with the MP piece include:

- Incorrect use of subscripts
- Incorrect use of molar mass
- Use of volume

Table 4.4
Subjects' Performance with the Mass Percent Piece

SBJ	MP									
	87%									
	NR	CD	UDI	DD	DSE	URH	UG	S	T	%
	8	2	13	15	0	0	0	98	113	
01	0	0	1	0	0	0	0	7	8	88%
02	0	0	1	1	0	0	0	6	7	86%
03	1	0	0	0	0	0	0	7	7	100%
04	1	0	1	1	0	0	0	5	6	83%
06	0	0	2	0	0	0	0	6	8	75%
07	0	1	1	0	0	0	0	6	8	75%
08	0	0	0	2	0	0	0	6	6	100%
09	1	0	0	0	0	0	0	7	7	100%
10	1	0	0	0	0	0	0	7	7	100%
11	1	0	0	1	0	0	0	6	6	100%
12	1	0	0	0	0	0	0	7	7	100%
13	0	1	0	1	0	0	0	6	7	86%
14	0	0	1	0	0	0	0	7	8	88%
15	1	0	0	0	0	0	0	7	7	100%
16	0	0	4	3	0	0	0	1	5	20%
17	1	0	2	4	0	0	0	1	3	33%
18	0	0	0	2	0	0	0	6	6	100%

Before talking about the common mistakes, I wanted to point out two students, Amelia (S17) and Vanessa (S16), who received the two lowest success rates from the MP piece. Amelia had the highest number of DDs and she got the MP piece just one time right by using trial and error method. In Problem 1, she clearly stated that she did not know (remember) how to calculate the MP. Although she had learned it before, she could not calculate the MP or use it to find the mass of the elements or compounds.

> S17: I do not know, because I do not precisely remember how to take a percent and how to get the percentage to mass because I forgot…I know it's just forgetting…just forget that its even a percentage and then you divide it either by the entire solution or just by the specific number of the element or atom…

Vanessa also got the MP piece just one time right but she made more mistakes than Amelia did. Vanessa calculated the MP four times incorrectly while Amelia got the MP piece 2 times incorrectly. It should not be interpreted as Vanessa had poorer understanding than Amelia did or vice versa. The real reason for that difference was Amelia's preference. She tended not to do the MP piece to avoid making mistakes. Therefore, compared to Vanessa, Amelia had fewer number of UDIs and her success rate appeared to be higher than that of Vanessa. It could be misleading information if we had looked at just this information on the tables and drew conclusion about their performance with the MP piece. This case showed that we needed to be extra careful and examine all the data before concluding about students' success with any piece.

Incorrect Use of Subscripts. Vanessa (S16), Gwen (S13), Bob (S14), Silas (S01) and Guillermo (S06) were among the students who used the subscripts incorrectly to calculate the MP. Vanessa, in both Exercise 5 and Problem 6, found the MP incorrectly using the subscripts of the elements. For example, in Problem 6, she simply calculated the MP of each compound in the mixture by finding the ratio among the subscripts.

> S16: (Reads question)…methane is CH_4 and ethane is C_2H_6. (Reading question again)…you have 4 hydrocarbons, 2 and 1 so we are 1 to 4 and 2 to 6 or 1 to 3 and it's 100 percent (doing calculations and reading question again)…there is 30 percent of carbon.
> I: How did you find that?
> S16: Because these are, wait…okay maybe I had better slow down. These are only 1 gram per mole, it does not matter what the grams per mole are, it is the mass percent…because the ratios are 1 carbon to 4 hydrogen here, 2 carbons to 6 hydrogen here and then when I add them together this is 10. 10 times 10 equals 100, so that is my 100 percent there and then this is 3 times 10 equals 30 percent.
> I: OK. That is how you got the number?
> S16: Yes, because out of that 100 percent my ratio is 1 to 4 and 2 to 6, which would give me 3. So, it would be 30 percent, because I have more hydrogen then I do the carbons.

It was clear that Vanessa did not have the MP piece well and did not know that subscripts tell the ratio between the numbers of particles of elements not the MP. Although it could be used to calculate the MP, it was not easy for students to link the micro world to the macro world. The students who did use the subscripts incorrectly to calculate the MP appeared that did not know that without considering the atomic mass of the elements or molar masses and their subscripts at the same time, it is impossible to get the right MP of elements in the compounds or MP of the compounds in the mixture.

If the question involves the mixtures, students should be more careful because, in the mixtures, subscripts mean nothing as you go from one compound to another compound or element. Bob apparently was one of those students, who did not know this fact and, therefore, failed in Problem 9. He tried to calculate the mass percent of Vanadium (V) in two compounds of Vanadium, V_3S_4 and V_5S_4 using the subscripts. He found the MP of

Vanadium in the V_3S_4 by dividing the subscript of V in V_3S_4 by the total subscripts of V in both compounds. He, then, reported his answer as 37.5% ((3/8)*100).

Incorrect Use of Molar Mass. The types of the errors and difficulties were not limited to the misuse of subscripts. There were also some students, who tended to use the volume and the molar mass incorrectly to calculate the MP. Guillermo (S06), Gwen (S13), Vanessa (S16), Yang (S18), and Silas (S01) are among those students who have poor understanding of molar mass of compounds and the MP piece. It does not necessarily mean that these students had the problem wrong but all showed that some misunderstandings regarding the MP piece and the function and the meaning of molar mass.

For example, Guillermo, in Problem 6, used the molar masses as the masses of the compounds and multiplied the MP of C_2H_6 by the molar mass of the C_2H_6 and the MP of the CH_4 by the molar mass of the CH_4 to find the mass of those compounds. In a similar way, Vanessa in Problem 11 multiplied the MP of Cl by the molar mass of the Cl to find the mass of the Cl. There are two possible explanations for their failure. They both possibly assumed that the number of moles of compounds were one or they had poor understanding of molar mass. Considering the fact that there was no information in the question telling that numbers of moles of the compounds were one, the second possibility looks more plausible.

Like Guillermo and Vanessa, Gwen, in Problem 6, did use the molar mass incorrectly but in a different way. She added molar masses of two hydrocarbons and their molecular formulas. She had a molar mass of 46 g/mol and a molecular formula of C_3H_{10}. Silas and Tammy (S04) did the same mistake and added the molar masses in Problem 9. It appeared that adding the molar masses of the compounds to make the calculations easier in finding the MP was a common mistake among the students.

Use of Volume. Although there were many students, who used the molar mass of elements or compounds incorrectly either for calculating the MP or for other purposes, there was only one student, Jason (S02), who tended to use the volume to calculate the MP. Jason (S02) tried to use the volume when he was not sure what to do to find the MP of the carbon in the mixture of methane and ethane in Problem 6. However, he realized that volume can be substituted for mass only with water (because water's density is 1.0 g/mL) and he changed his method and then could solve the problem correctly.

> S02: I am just going to say I have 10 ml of solution. 40% would be 4 ml of Methane and 6 ml of ethane…

Jason did those calculations but he was not comfortable with his solution and, later, changed his method.

> S02: I do not know if it will work to approach it that way either because I am not sure how many, because water is you can equate 1 gram of water to 1 ml of water but you can not do that with other stuff.

He realized that he was making a mistake in calculating the MP and corrected himself. In the end, he got the right answer. Although the use of volume to calculate the MP was not a common mistake, I wanted to bring into readers' attention because it could be a common problem with a larger group of students.

Checking the Solution not Only the Answer. Jason's solution reminded us an important factor and technique to get the right answer and be successful in problem solving. Checking the solution as the person proceeds towards an answer is an important characteristic of the expert way of problem solving. It is important to check the answers at the end but it is more important that problem solver evaluates and assesses every step while solving the problem. By this technique, problem solver can increase the chance of getting the right answer.

Since most students did not evaluate their MP solutions while working on them and left the checking to the end or did not check at all. Jason and other few students, however, did check their solutions, corrected themselves, and found the right way to calculate the MP since they were checking their solutions while processing.

Faith was one of the students, who found her own mistake and ended up with a successful solution in Exercise 5. She, to find the percent of elements in glucose ($C_6H_{12}O_6$), first tried to calculate the MP using the subscripts of elements but realized that the number she found did not make

sense. Then, she tried to divide the total mass by the mass of elements but again realized that the new answer did not make sense either. Finally, she found the right way and divided the mass of each element by the total mass to find MP of each element and percent composition of the compound.

> S15: All the different number of moles is 24. That is what I was thinking, but I do not think that's right because I have to take into account the grams of each, so actually I think I want to take 180 divided by 72 to get the carbon (doing calculations)…which only gives me 93.7 percent, which does not sound right. (Doing calculations)...it gives me 100 percent, I just added wrong so that is my answer.

Although the checking the solution step by step while working on it looked like an efficient method to determine the mistakes and get rid of them, it is perceived a difficult task to do because of the limitations on working memory capacity. We can only process a certain amount of the information at a time. This is more difficult for the novices since their knowledge is in pieces. Their problem solving uses their all available mental sources and working-memory capacities. On the other hand, successful problem solvers and, especially, experts have the chunks of the knowledge connected each other with strong bonds and collected around the principles and concepts. Therefore, the problem solving does not take too much of their working memory capacities. As a result, they do not have too much difficulty while checking their answers in solving the problems.

Empirical Formula (EF) and Molecular Formula (MF)

What the EF and MF are and How They are Found. Our next two pieces are the empirical formula (EF) and the molecular formula (MF). While the empirical formula is the simplest atomic ratio of the elements in a compound, the molecular formula is the true number of atoms in a compound. The empirical formula and the molecular formula can be the same, or the molecular formula can be any positive integer multiple of the empirical formula. Examples of empirical formulas are AgBr, Na_2S, and $C_6H_{10}O_5$. Examples of molecular formulas are P_2, C_2O_4, $C_6H_{14}S_2$, H_2, and C_3H_9.

Most of our subjects in this study had difficulties in determining the empirical formulas even when given the number of moles of elements making up the compound. This is perhaps because this "piece" often requires the connection of several pieces: the percent composition, the number of moles, and the empirical formula. In their attempts we noticed that some of our subjects appeared to not have a good understanding of the particle nature of matter would not use the explanatory power of the particles until they were told to do so.

Overall Performance on the EF. Our subjects were not as successful with EF as they were with other pieces. They had a success rate of 54% for this piece, which was the lowest score among all other scores they got from all the pieces.

As Table 4.5 shows, they got 16 UDIs, 7 DDs, and 22 Ss out of 41 trials. At least, some of the students did not have this piece at all. Subjects, Tammy (S04), Faith (S15), and Amelia (S17) got a success rate of zero while Silas (S01), Jason (S02), and Bob (S14) got a very low success rate, 33%. Therefore, we might assume that these students will have difficulty while dealing the problems, which involves EF piece, and get lower scores from those problems.

Table 4.5
Subjects' Performance with the Empirical Formula Piece

SBJ	EF									
	54%									
	NR	CD	UDI	DD	DSE	URH	UG	**S**	**T**	%
	1	3	16	7	0	0	2	**22**	**41**	
01	0	0	2	0	0	0	0	1	3	**33%**
02	0	1	1	0	0	0	0	1	3	**33%**
03	1	0	1	0	0	0	0	1	2	**50%**
04	0	1	1	1	0	0	0	0	2	**0%**
06	0	0	1	1	0	0	0	1	2	**50%**
07	0	0	1	1	0	0	0	1	2	**50%**
08	0	0	1	1	0	0	0	1	2	**50%**
09	0	0	1	0	0	0	0	2	3	**67%**
10	0	0	1	0	0	0	0	2	3	**67%**
11	0	0	0	0	0	0	0	3	3	**100%**
12	0	0	0	0	0	0	0	3	3	**100%**
13	0	0	0	1	0	0	0	2	2	**100%**
14	0	0	2	0	0	0	0	1	3	**33%**
15	0	0	2	1	0	0	0	0	2	**0%**
16	0	0	0	1	0	0	1	1	1	**100%**
17	0	0	2	0	0	0	1	0	2	**0%**
18	0	1	0	0	0	0	0	2	3	**67%**

Typical Difficulties and Mistakes with the EF. The difficulties determined from the subjects' problem solving trials showed a variety:

- Difficulty in remembering the meaning of empirical and molecular formula and differentiating the formulas from each other
- Using the incorrect methods to find the empirical formulas such as using the mass of the elements instead of using the number of moles,
- .Difficulty in figuring out the ratio among the number of elements while determining the empirical formula.

Difficulty with Retrieval of the Meaning of the EF. Most of the students did not know or remember correctly what the EF means and how it differs from the molecular formula.

Nine of the subjects needed the meaning of the empirical formula as a hint to go further; otherwise, they could not do anything. Jason (S02) was one of the nine subjects received the hint. When I asked Jason the meaning of the empirical formula before he had attempted to solve Exercise 6, he tried very hard to remember the definition of the EF but all his efforts were useless.

> I: Do you know what the empirical formula is?
> S02: You know I was supposed to learn it at one time and I probably did but it just escapes me right now exactly what empirical formula means.
> I: Do you remember anything about it?
> S02: I actually remember almost nothing about it. I know it… I know it is a reduction from the original of some kind… I mean it is making it simpler somehow... but I am really not sure. I cannot remember what empirical means. I was kind of hoping we would cover it again this semester so I could re-learn it but we have not got there, so…

After the hint, however, he solved the question easily and got the right empirical formula for the sodium per chlorate. Like Jason, Silas (S01), Aubrey (S07), Santiago (S12), Gwen (S13), and Vanessa (S16) got the right formula in Exercise 6 after the hint. On the other hand, despite the hint, Brooklyn (S03), Faith (S15), and Amelia (S17) could not find the right formula. It indicates that *determining the EF does not only depend on the knowledge but also the ability to deal with the ratios*.

Effects of the Hints in Retrieval. In general, we can say that the hints were not always helpful and some students could not use the hints and make sense of them as well. Either the hints provided were not the pieces students were looking to complete their solutions or students focused too much on something else. Therefore, they were not really hearing what I was telling and explaining them. Brooklyn (S03) showed a similar behavior and continued what she had been doing before the hint.

> S03: So, it does not help me with this problem...cause
> I: Are you saying the definition of the empirical formula did not help you?
> S03: Yes… I can find the mass percent this way...but I wonder if… In that last problem, it did not help me because it was the same numbers...so I mean...ok if I can find mass percent. Let us just get back to this...cause this many grams per this is what I have in my...I know I have to work backwards...I just can't think how...how to do it...

Rather than focusing on the hint, she tried to retrieve the procedure she followed in the previous question regarding the MP piece. She thought that method would work in this problem, too, because it worked before. This is a

common mistake that students do while solving the problems. They transfer the methods and procedural knowledge without considering the context of the question. Those students appear to be more pattern followers, rather than conceptual learners. I do not mean that transferring the procedures is totally incorrect or inefficient method to solve the problems. Actually, we need to transfer and retrieve the procedures but it should be done as experts and successful problem solvers do, transferring the procedures not as individual pieces, rather, more like chunks, which compromise the procedural and conceptual knowledge. Steve (S11) did transfer the procedural knowledge from other questions to Exercise 6 but it was not separated from the concepts attached to it.

> S11: (Reading question). To find the empirical formula, you're basically finding the moles of each… want to find the moles of each, then you make a ratio and can find the empirical formula. 2.82g sodium times mol, divided by 22… equals .123 mol of Na…. 4.35g Cl times a mol, divided by 35.5 g/mol equals .123 mol of Cl, then 7.3 g O times a mol divided by 16g equals .489 mol of O. So these are basically the same, so it will be the coefficient for- it will be one mol Na, then one mol Cl, per um, .489 mol oxygen divided by .123 mol chlorine… and you get 4 mol oxygen per mol chlorine, so you would have um, Na, O4… NaClO4…

Unfortunately, not everyone was as successful as Steve (S11) in retrieving the knowledge to determine the EF of the sodium per chlorate. Some remembered that they had to find a ratio to determine the EF but they were not sure whether they needed to use the mass of the elements, the MP of the elements, or the number moles of the elements.

Incorrect Methods with the EF. There were a few students, who did mistakenly use either the mass of the elements or the MP of the elements. Kristen (S10) in Problem 3, Vanessa (S16) in Problem 11, and Faith (S15) in Exercise 6 and Problem 11 made these mistakes. They did not know either the meaning of the empirical formula or the fact that each atom has a different atomic weight. Thus, the ratio among the mass of the elements or the MP of the elements cannot provide the empirical formula.

Faith (S15) determined the EF by getting a ratio among the MP of the elements in Problem 11 and the mass of the elements in Exercise 6 although she received the hint about the meaning of the empirical formula. In Problem 11, I asked her if she knew the empirical formula and she tried to give me a definition but it was not clear. Thus, I defined it for her.

> I: Do you know what the empirical formula is?
> S15: Yes I do.
> I: What is that?
> S15: The one is with the N and stuff in there.
> I: What is N?
> S15: It is the ratio of them to each other.
> I: What kind of ratio? The ratio among what?
> S15: …
> I: I can give the definition. The empirical formula is the one, which shows the simplest mole ratios between the elements in the compound.

She could not make sense of the hint or integrate the extra information since she had already been dealing with so many pieces. She sounded that she was using her working-memory capacity in full.

> S15: There is too much information there. It is all running together and confusing me. So, 55 percent of the 9 grams should be chlorine.

> So, 9 grams contains less than 1 mole of hydrogen. I can see it all in my head even clearer today than last time about how to do this from last semester. It is just this little chart and I cannot remember it still. I know it had something to do with percents. My mind is so blank.

It was surprising to hear that she was still thinking that EF has something to do with the mass percent after I had defined the meaning of the EF. She did not calculate the mass percent of the elements to find EF in Problem 11, instead, used the mass of the elements to find the ratio and the empirical formula. She calculated the mass of C, Cl, and H as 3.35g, .696g, and 4.95g, respectively. Then, she determined the ratio as 5:1:7 and determined the EF as C_5HCl_7. On the other hand, in Exercise 6, she used the mass percents of the elements to determine the EF. She apparently did not have the EF piece. One thing really caught my attention about Faith's solutions related to EF was that she never failed in dealing with the ratios. She had the ability and the knowledge to deal with the ratios – but did not consistently deal with ratios of moles.

Difficulty with Ratios. Besides the students who did not know what to use to find the ratio, there were other types of students, who were not able to deal with the ratios. Some of the students had difficulty with the ratios were Silas (S01), Aubrey (S07), Amelia (S17) and Bob (S14). While Silas and Aubrey in problem 11 and Bob in exercise 6 did find the incorrect ratios after finding the right number of moles of the elements, Amelia (S17), in Exercise 6, could not find any ratio and could not provide an answer. In Exercise 6,

Bob provided an incorrect EF and I did try to find what happened so that he presented $NaClO_2$ as the EF instead of $NaClO_4$.

> S14: That's the number of moles of chlorine. There are relative to moles of oxygen since these are all the same. To give me an approximation of how much of each there is, so there are, is essentially 4 time as much oxygen as there is chlorine, which means there's 4 times as much oxygen as there is sodium, so that would mean I would need 2 of these and 2 of these to get 4 of these, or 1 of these and one of these to get 2 of these, so Na sodium Cl and oxygen in a compound, sodium chlorine oxygen. I have never seen oxygen in anything with sodium and chlorine. The only thing I can think of with that is salt, one of these, one of these gives me one of those, no 2 of these, one of these one of these…
> I: How did you find that 2?
> S14: (Mumbling) How did I find?
> I: Yes, that 2.
> S14: Oh, I was just, the that was just multiplying the moles of that times by 2 to see what the mass was for that...
> I: Just trying?
> S14: Yeah, just looking at it trying to think of what I need to do next, because I can't think of any compounds of sodium and chlorine with oxygen in them, I have 4 times as much oxygen as each of those, so I would need 2 and 2 of those, so I need, looking for the lowest number that would be 2, put that on the wrong one, 4 times that to get 2 of those and 2 of those give me 2: 1: 1.

Unfortunately, the reason for his choice was not still clear after many probing questions. I could not reach the root of the problem. He sounded more he used the trial and error method to make sense of the compound since he had not been familiar with that type compound as he stated.

Lady (S08) and Nanette (S09), on the other hand, made different mistakes from the others. Lady, in Exercise 6, found the number of moles of Na, Cl, and O and the ratio among them correctly but used that ratio incorrectly. She found the ratio as 1:1:4 and multiplied everything by four

and got the $Na_4Cl_4O_4$ instead of making the EF as $NaClO_4$. Nanette, in Problem 11, instead of trying to find the ratio among the elements, rounded the number of moles of the elements and used them as subscripts in the EF. She got the number of moles of Cl, H, and C as .139 mol, .696mol, and .280mol respectively. Then, she rounded them as 1, 7, and 3 and made empirical formula, C_3H_7Cl.

Summary of the EF. The analysis showed a great variety in terms of the difficulties and problems that students encounter and have while doing the EF piece. After the analysis, it got clearer why the success rate for this piece was the lowest. There were students, who had either poor knowledge of EF or difficulties especially dealing with the ratios involved more than two numbers or decimal numbers, and there were students, who did not remember the meaning of empirical formula and how it differs from the molecular formula at all.

The Similarity and Difference between Performances on the EF and MF. As the meaning of the empirical formula, the meaning of the molecular formula was not clear to students. Eleven students needed the definition of the molecular formula as the hint. Although the number of the hints for the molecular formula was greater than that of the hints for the empirical formula, students showed much better performance with the molecular formula. They, in average, had a success rate of 88%. This success rate compared to the success rate of the EF, 54%, is very high.

There might be different reasons for the difference between the success rates of the EF and the MF. One reason is that the students had to determine the EF three times and the MF just one time. The question might not be a very good indicator of their performance with the MF piece. They could have a greater or lower score with greater number of questions but we cannot know this now. This might be considered as a limitation to the study.

Table 4.6
Subjects' Performance with the Molecular Formula Piece

SBJ	MF									
	88%									
	NR	CD	UDI	DD	DSE	URH	UG	S	T	%
	0	1	1	0	0	0	0	15	17	
01	0	0	0	0	0	0	0	1	1	100%
02	0	0	0	0	0	0	0	1	1	100%
03	0	0	0	0	0	0	0	1	1	100%
04	0	1	0	0	0	0	0	0	1	0%
06	0	0	0	0	0	0	0	1	1	100%
07	0	0	0	0	0	0	0	1	1	100%
08	0	0	0	0	0	0	0	1	1	100%
09	0	0	0	0	0	0	0	1	1	100%
10	0	0	0	0	0	0	0	1	1	100%
11	0	0	0	0	0	0	0	1	1	100%
12	0	0	0	0	0	0	0	1	1	100%
13	0	0	0	0	0	0	0	1	1	100%
14	0	0	0	0	0	0	0	1	1	100%
15	0	0	0	0	0	0	0	1	1	100%
16	0	0	1	0	0	0	0	0	1	0%
17	0	0	0	0	0	0	0	1	1	100%
18	0	0	0	0	0	0	0	1	1	100%

The other reason for the better performance with the MF piece might be that the students did not have to deal with ratios to find the MF. Students, who had difficulty in determining the EF, did not have trouble at determining the MF. Since we provided the definitions (in these cases, URH was not assigned because simply providing a definition was not considered a hint) to complete the pieces, I assume the differences mostly come from their abilities dealing with the ratios. Research (Dawkins, 2003) indicates that there is a correlation between the students' performance in problem solving in stoichiometry and their proportional reasoning abilities.

Typical Difficulties and Mistakes with the MF. We actually did not observe any significant difficulty on students' part. Students did show very good performance with the MF piece. Only two students, Tammy (S04) and Vanessa (S16), had difficulty with MF. Tammy attempted to find the MF but could not finalize the solution. She could find the number of the moles of elements by using the mass percents but could not determine the MF. On the other hand, Vanessa finalized her solution and provided a MF but it was incorrect. Although Vanessa worked hard to determine the right MF, she could not get the right one. She tried several methods but none of them did work for her.

> S16: Lactic acid is 90.08 grams per mole and you have 40 percent carbon. So, it would be 40 carbon, 12 grams, 6.71 percent hydrogen, which is 1 gram and 53.3 grams of oxygen, which is 16 grams (doing calculations)…which would give you 480 grams of carbon (doing calculations)…67.1 grams of hydrogen (doing calculations)…852.8

> grams of oxygen (doing calculations)…6202.88, I'm going way off here (doing calculations) equals 68.85, which is wrong. Now let me see…
> S16: 12 divided by 40 and then 1 divided by 6.71 is .149 and then 16 divided by 53.3 is .300. Its 40 percent (doing calculations)…now I am going off on this again. It is 90.8 grams per mole, so this needs to equal 90.08 grams per mole. 40 percent of it is carbon (doing calculations)…so that means I would have 13 hydrogen, 2 carbons and almost 2 oxygen… So, this would be 24 grams of carbon, 13 grams of hydrogen and 2 grams of oxygen. (doing calculations)…$C_{13}H_{12}O_2$.
> I: So how did you come here. You found the .3 by dividing the 12 by 40 and then how did you come up with the 2 point…
> S: 2.52?
> I: Yes.
> S16: 2.52, how did I come up with that? 90.08, because there is 90.08 grams per mole divided by 40 percent and that gave me 2.52, which I round out to 2 grams, which gave me 24 grams on my carbon and I did the same thing here, which gave me 13.42, so this should actually be 13 and then I did the same here and divided the 90.8 by 53.3, which gave me 1.69, which I round off to 2 and that have me $C_2H_{13}O_2$.

Vanessa sounded like she was not sure what she was doing. She was acting as an algorithmic thinker. She worked for an answer and got one. That was the important thing for her. She did not explicitly check her answer to see if the answer made sense or not. On the contrary, seven students in this question checked their answers conceptually if they made sense and three of them checked the answers mathematically. These numbers were high numbers compared to the numbers of students checked their answers in other questions. It could be interpreted in two different ways: students probably did find the question very easy or students really had a good understanding of MF.

Summary of the EF and the MF. We concluded that the students had a good understanding of the MF piece but not the EF piece. Although most of

the students had the MF piece all the time, only a few students got the EF piece right all the time. The rest of the students split into two groups. The students in the first group got the piece either right or wrong depending on the context and the nature of the question. The students in the second group never got the EF piece right depending on possible factors such as the poor knowledge of the meaning of the EF or the inability of dealing with the ratios.

Percent Yield (PY)

What the PY is and What its Components are. The term *percent yield* is used to indicate how much of a desired product is obtained from a reaction.

Percent yield = (actual yield of product/ theoretical yield of product) x100

The theoretical yield from a reaction is the yield calculated by assuming that the reaction goes to completion, all reactants are pure, and the reaction does not form undesired products. On the other hand, the actual yield is the amount of a specified pure product actually obtained from a given reaction. As it is seen in the definitions, the percent yield has three important components, which needed to be studied in order to have a better understanding of the students' performance with the PY piece.

These three components are being able to identify the actual yield (PYAC), knowing what substance and amount to use in order to calculate the theoretical yield (PYTH), and having the skill and knowledge to put them

together in the formula and carry out the solution (PYF). Briefly, the issue is not only being able to use the formula of percent yield correctly or not. The key in succecss with the PY is to do all the compoenents successfully at the same time.

Therefore, we examined and explored the students' difficulties with the PY piece from a wider angle. We also separately investigated the PYAC , PYTH, and PYF components to obtain more insight and information about students' performance with the PY piece.

Overall Performance on the PY. The students' achievement was not very good compared to other pieces. Except the EF, all other pieces had a better average success rate than the PY piece. The analysis helped us to understand the low success rate of PY piece. Among the three components of PY, students had the most difficulty with PYAC. Students in most questions did the PYAC component incorrectly. For example, in Problem 2, nine, in Problem 12, seven of the students got this component incorrect . Students' poor performance with the PYAC in Problems 2 and 12 lowered the success rate of the overall success rate of the PY piece to 68%. Moreover, having different number of students who got the PYAC incorrect in different questions indicated that contexts of the questions and the interaction among the pieces could be responsible for the low score of the PY.

Table 4.7
Subjects' Performance with the Percent Yield Piece

SBJ	PY									
	68%									
	NR	CD	UDI	DD	DSE	URH	UG	**S**	**T**	**%**
	44	2	19	8	0	0	1	**44**	**65**	
01	2	0	1	0	0	0	0	2	3	**67%**
02	2	0	2	1	0	0	0	2	4	**50%**
03	5	0	0	0	0	0	0	5	5	**100%**
04	2	0	1	0	0	0	0	2	3	**67%**
06	3	0	2	0	0	0	0	3	5	**60%**
07	5	0	0	0	0	0	0	5	5	**100%**
08	2	0	1	1	0	0	0	2	3	**67%**
09	3	0	1	0	0	0	0	3	4	**75%**
10	4	0	1	0	0	0	0	4	5	**80%**
11	3	0	1	1	0	0	0	3	4	**75%**
12	2	0	2	1	0	0	0	2	4	**50%**
13	1	0	2	1	0	0	0	1	3	**33%**
14	3	1	1	0	0	0	0	3	5	**60%**
15	2	0	2	1	0	0	0	2	4	**50%**
16	0	0	2	1	0	0	1	0	2	**0%**
17	2	1	0	1	0	0	0	2	3	**67%**
18	3	0	0	0	0	0	0	3	3	**100%**

Typical Difficulties and the Mistakes with the PY. We observed different difficulties in students' solutions about the PY and made some common mistakes. These difficulties were as follows:

- Diffculty in Retrieving of the formula of PY
- Difficulty with using the formula-PYF
- Difficulties with finding the PYAC and PYTH

Difficulty with Retrieval. The first and most common problem with PY piece, like with other pieces, was that students had great difficulty in retrieving the information about the PY piece although they often did calculations regarding the PY while they were writing their reports for the experiments. In Exercise 8, eleven and, in Problem 2, again nine students needed to be reminded the formula of percent yield. It appeared that retrieving was a common issue in learning and problem solving. Students needed to retrieve a formula, a symbol, or an equation to solve problems but they were not successful at retrieving the necessary pieces for their solutions. It might be due to two main reasons. Students possibly could not learn those pieces well at first place or they did learn but they could not retrieve since they did not have an organized knowledge. Depending on their success with using the formula of PY after the hint, I am thinking the problem is more like having an unorganized knowledge.

Difficulties with the PYF. Besides the difficulty of retrieving the formula of PY, students also had difficulty at differentiating the percent error formula from the percent error formula. Silas (S01), Amelia (S17), Gwen (S13), Steve (S11) were four of them, who did mixed up the formulas. Some of those students, themselves, realized that it was not the formula of percent yield and changed it with the right one while some needed more guidance and received the right formula from me. After receiving the formula of the percent yield, the issue was if they would plug the numbers, for PYAC and PYTH

correctly into the formula or not. Except Nanette (S09), Amelia (S17), and Vanessa (S16), students were overall successful with PYF. Vanessa, in Exercise 8, did calculate the percent yield by dividing the molar mass of silicon carbide by its actual mass. Amelia in the same question did divide a number that she defined as theoretical yield of SiC and divided by the actual yield of SiC to get the PY. In the same manner, Nanette, in Problem 2, divided the theoretical by the actual yield and got an incorrect PY for the reaction. The mistakes regarding the use the formula of PY were rare compared to the mistakes done regarding the PYAC and PYTH components.

Difficulties with the PYAC and the PYTH. All but three students got either PYAC, PYTH or both pieces wrong at some point. In Exercise 8, Vanessa (S16) and Amelia (S17) got both pieces incorrectly while, in Problem 12, Jason (S02), Steve (S11), and Santiago (S12) and, in Problem 2, again Vanessa (S16) got the both pieces wrong. Although they occasionally got one piece right when they got the other one wrong, it appeared that if someone got either one of the pieces, PYAC or PYTH, incorrect, they most likely he got other one incorrect too, because they mixed up them, or did not do anything for the second piece. In the second problem, Faith (S15) did do PYAC piece correctly while she got the PYTH piece incorrectly. She used the molar mass of N_2O_4 instead of its given mass to calculate the theoretical yield of N_2. Lady (S08), Silas (S01), and Tammy (S04), on the other hand, got the PYTH piece right and PYAC wrong. Since they did not consider the side reaction and do

proper calculations, they got incorrect PYAC. Although they got the both PYTH and PYAC correctly in Exercise 8, they could not get either the PYAC piece or the PYTH piece right in Problem 12.

It did not mean that they did not have those pieces; rather, it was evidence showing that the nature of the questions and ability to link the pieces were the important factors in getting a problem right or wrong. In addition to common mistakes regarding PYTH and PYAC components, such as mixing the actual yield with theoretical yield, accepting irrelevant figures as theoretical yields or actual yields, and dividing theoretical yield by actual yield, there were also some misunderstandings about the meaning of PY piece.

A Misunderstanding about the PY. Many students incorrectly calculated PY piece to be greater than 100%. Their reaction with that answer showed differences. Some of them understood that they did something incorrectly and attempted to change their answers by checking their solutions and recalculating the PY. Some were successful and some of them were not. Bob (S14) was one of those students, who realized that he made a mistake and questioned his solution but were not successful at finding the right answer.

> S14: Actual yield.. (writing)... (mumbles).. agree and there should be some reactant left in there, in the product.. (reading the question). I am guessing this percent yield is supposed to be the same percent yield as the one given, so 7. What would be the actual mass... the same percent yield... um, that is kind of throwing me off there, because the

> uh % yield of 7…7.74 divided by 7.39 is 100 and uh, essentially 100 and say, roughly 105% yield…
> I: So, what do you think?
> S14: That would be the actual mass; they both have the same percent yield... CO2... um, what would be the actual mass... well, they can't both have a 105% yield... um,
> I: So is it possible for this reaction to have greater than 100% yield?
> S14: If that's, given a balanced equation of everything that should be reacting.. no, it shouldn't have 100% yield.. because at that point you're conjugating matter out of nothingness.
> ……
> S14: Assuming that that is completely reacted, this is what would have been, what would give me 105% yield, it's just a way to show that something's not right... because the percent yield is over 100.

On the other hand, although some were hesitant with their answers, they thought it was all right to get a percent yield greater than 100% and brought different explanations for those percent yields. Faith (S15) was hesitant at first but then decided that it was all right to have that high percent yield because she had before in the experiments.

> S15: This is expected and this was what was actually, that is a higher number than that, so I am going to have more than 100 percent.
> I: Is it impossible?
> S: No, it is not impossible, but that would be the highest percent yield would be more than 100 percent is what I am getting based on what I just did. It is not impossible because it has happened before on experiments so I will just go ahead and do it (doing calculations)…so I am getting 103 percent.
> I: So, you are saying that it is possible.
> S15: It is possible… it is possible.
> I: You were hesitant…
> S15: Just because I am not sure if I did it right. I know it is possible and that could be the correct answer, but I am not sure that it is.

Jason (S02) also was unsure with his answer but then thought it is possible to have that PY by bringing a different explanation from the one Faith brought up.

> **S:** Well, the student got 7.74 grams when they should've had 7.392 so they actually got more than they were supposed to, which it does happen, it happens once and a while, I'm not sure how it doesn't seem possible but it does happen...(calculating) so the actual yield or the actual % yield 104.71%, what would be the actual mass
> **I:** So, it is 104%. Does that make sense to you?
> **S:** That makes sense to me because the person ended up with more than they should have so it should be over 100% and they're really close. Therefore, 104 seems reasonable.

Although the explanations that the students provided were different from each other, they indicated that students had a misunderstanding with the PY piece.

Summary of the PY. Especially some students like Vanessa (S16) and Amelia (S17) did not have this piece fully. The analysis showed that many students had difficulties and those difficulties were diverse but were not limited to those mistakes. There were also some students, who were not aware that they had to determine the PY piece before they went further in their solutions. I had to assign DD code eleven times for the PYF piece. Like with PYF piece, many students had forgotten to consider the limiting reagent in the problems until they were reminded to do so. In the following section, we are going to explore students' performance with the limiting reagent and learn more about the sources of the difficulties that students encounter while

determining the limiting reagent in stoichiometry problems.

Limiting Reagent (LR)

What the LR is. Sometimes when reactions occur between two or more substances, one reactant runs out before the other. That is called the "limiting reagent". Many first-year chemistry students have trouble with basic stoichiometry problems involving a limiting reagent (Kalantar, 1985).

Overall Performance on the LR. Although the students in this study made some mistakes while trying to determine the limiting reagent they were successful overall. Out of 25 trials, twenty of LR attempts were correct for a success rate of 80%.

Forgetting to Consider the LR. Often, it is necessary to identify the limiting reagent in a problem as a first step before doing other calculations. This study shows that students sometimes simply forget this step. When they do skip this step, students often proceed to struggle with what to do with the given amounts of the reactants and which one to use in solving the problems. Some did try to use both and some chose one of the reactants seemingly arbitrarily. For example, Silas (S02) used both reactants in Problem 2. He first found the number of moles of the N_2H_4 and N_2O_4 but in the rest of the problem, he did not use those numbers of moles. Instead, he used the coefficients of the N_2H_4 and N_2O_4 as the numbers of moles to get the mass of

the N_2. Therefore, at the end, he got the same mass of N_2 from each one and could not detect his own mistake.

Table 4.8
Subjects' Performance with the Limiting Reagent Piece

SBJ	LR									
	80%									
	NR	CD	UDI	DD	DSE	URH	UG	S	T	%
	0	0	5	9	0	0	0	20	25	
01	0	0	1	1	0	0	0	0	1	0%
02	0	0	1	0	0	0	0	1	2	50%
03	0	0	0	0	0	0	0	2	2	100%
04	0	0	0	1	0	0	0	1	1	100%
06	0	0	0	2	0	0	0	0	0	NA
07	0	0	0	1	0	0	0	1	1	100%
08	0	0	0	1	0	0	0	1	1	100%
09	0	0	0	1	0	0	0	1	1	100%
10	0	0	0	0	0	0	0	2	2	100%
11	0	0	0	0	0	0	0	2	2	100%
12	0	0	0	1	0	0	0	1	1	100%
13	0	0	1	0	0	0	0	1	2	50%
14	0	0	0	0	0	0	0	2	2	100%
15	0	0	0	0	0	0	0	2	2	100%
16	0	0	1	1	0	0	0	0	1	0%
17	0	0	1	0	0	0	0	1	2	50%
18	0	0	0	0	0	0	0	2	2	100%

Because there were several students who did not consider and determine the LR before doing the rest of the problem, I used the DD code nine times. This number might be higher if I had not been reminded ten students to consider determining the limiting reagent in the first question (Exercise 9) related to the LR piece. Except one of those ten students, after the prompt (in these cases, URH was not assigned because reminding

students to consider the LR is not a hint about how to do the LR piece), all checked their answers and determined the limiting reagent either correctly or incorrectly. In the second question (Problem 2) in which students needed to find the LR, again, eight of them did not consider the limiting reagent, either. As a result, I had to assign DD codes nine times.

Guillermo, before I mentioned about the LR, just chose the one of the reactants whose ratio was easier to deal for his solution. Based on the following reaction in Exercise 9:

$$2N_2H_4 + N_2O_4 \rightarrow 3N_2 + 4H_2O$$

He chose the N_2O_4, which had a ratio 1:3, instead of choosing the N_2H_4, which had a ratio of 2:3 with the N_2 to solve the problem but without worrying about the LR.

> S06: … this is N_2O_4 and then from there because this is a one to three ratio instead of two to three... I chose to go with N_2O_4...
> I: Why did you choose one to three ratio instead of two to three ratio?
> S06: because if I were to choose two to three I would have to multiply by 3 and then divide by 2...
> I: So, you are saying you chose the N_2O_4 to avoid complex math.
> S06: yeah...and this would just be the easiest way to do it.

When I asked him if he needed to consider the LR for this question, he, after little hesitation, decided that it was not necessary.

> S06: No...well the oxygen I don't know... if you are looking it would...limiting reaction is something you can leave out of the problem after I know that...and it really doesn't have anything to do with the reaction...but everything seems to have something to do with the reaction...well the nitrogen since it's singled out. It could be the limiting agent because make any bonds after the fact besides to itself...I think that is where my thinking is going...

> I: So, you think we do not need to worry about the limiting reagent for this reaction.
> S06: Yeah...

His explanation was not complete and clear. He sounded that he had a poor understanding of the LR piece. Guillermo again in Problem 2 did not determine the LR because he thought it was not necessary to find it.

> I: so here you are using just the N_2O_4 you kind a…you don't use the N_2H_4 the reason for that?
> S06: N_2H_4…umm…it's not really important to the reaction…well it is…it's taking the oxygen…but for what they're asking it's not really useful…

Since, in both questions, he did not attempt to find the LR, we could not assess his LR piece. We were not sure if he had this piece or not in a way that we defined in this study but he obviously had misconceptions about the LR piece. There were other students, who had misconceptions about the LR and difficulties with determining the LR, too.

Typical Difficulties and Mistakes with the LR. Students, as in other pieces, again did some mistakes and had some difficulties while doing the LR piece although they in general showed a good performance with LR piece. Those difficulties and mistakes included:

- Difficulty dealing with molar ratios
- Incorrect reasoning used in determining the LR

Difficulty with Ratios. The most common difficulty students encountered while trying to determine the LR was about dealing with the

proportions of the moles. It was especially frustrating for students when the reaction's stoichiometry was not 1:1.

Incorrect Reasoning used to determine the LR. In addition to the difficulties with dealing ratios, there were difficulties about remembering the right method and tool to use in order to determine the limiting reagent. For example, Jason (S02), in Problem 2, himself realized that he needed to find the LR after reading the part " 100 grams of each" in the question but could not remember whether he needed to use the mass or the number of moles of reactants to find the limiting reagent. He, finally, decided that the number of moles should be used but chose the N_2O_4 as his LR since it had a ratio 1:6 with the NO in the reaction, $N_2O_4 + 2N_2H_4 \rightarrow 6NO + 2H_2O$.

> S02: .....100 grams of each reactant, well there's only 1 mole N_2O_4 so that may be a limiting reactant, it may be or could be, I'm going to go ahead and assume that it is, because…well...formula weight here would be 28 32, and this would be, that's a lot heavier, 32.....
> I: What are you thinking now?
> S02: I'm thinking which one has to be the limiting reactant, I always stumble with this, 'cause I can never remember if it's moles I go by or if it's grams I go by, I just never remember, I think it's moles, I'm pretty sure you look at the moles first, I'm going to go ahead and say that the N_2O_4 is the limiting reactant and just say it's a 1 to 6 ratio, so .33 divided by 6, .056 moles and 204 (calculating) Ok, but that gives me 100 grams, it tells me 100 grams was used. I'm not sure how that, I mean I'm sure it makes sense but I'm not sure how?

Although he chose the right reactant as his LR, his reasoning and method were not right. His transcript and solution showed that he did not have this piece fully. He was not sure what he was doing. He certainly did have poor understanding of LR piece. Another student, who did not have LR piece fully,

was Gwen (S13). She also, in Problem 2, considered the LR without being reminded but her reasoning was incorrect

> S13: …okay so what I found is that nitro hydrogen is limiting because it has less of moles. So if I take 100 grams of…and you know the molarity and then…

She chose the one as her LR with the less number of moles without considering the coefficients. The incorrect methods were not limited to the ones applied by Jason and Gwen. Tammy (S14) in Problem 2 decided to determine LR after she was struggled with two different masses.

> S04: I do not know how to get from like there to or from here to there…I do not know how to get…I do not know where to start actually…I do not know if I use both of those or just one…well actually it would be 200 grams…that does not make any sense…well ok N_2O_4 so maybe this is a limited reactant problem…I do not know…4 times 16 for moles so 92 grams per one mole N_2O_4 so then that produces supposed to produce 3 of these…so does that mean this numbers are wrong…
> I: No, they are right.
> S04: so then one mole of N_2O_4 produces 3 moles of N_2…ok…doing calculations…moles of N2..so 10 grams of NO_4…maybe I was supposed to do this first…oh well it does not matter…100 grams of N_2O_4 is 92 per one mole of N_2O_4
> I: You preferred to go with the N_2O_4. What did you think when you decided to go with the N_2O_4?
> S04: because NO has an O in it…and nitrogen oxide has an oxygen in it…so that's why I used it…I do not know…I mean I do not know…

She determined the LR correctly but again her reasoning was completely incorrect. She chose the N_2O_4 as the LR since the N_2O_4 had oxygen in its structure like NO does. Other false reasoning and methods used by Vanessa (S16) and Amelia (S17). Amelia, in Exercise 9, compared the mass of the

N2H4 to the mass of N2O4 and chose the N2H4 because it has less mass. She employed the following method and explained her reasoning vaguely.

$$2N_2H_4 + N_2O_4 \rightarrow 3N_2 + 4H_2O$$

Start: 100g 200g
Use: 100g 100g
End: 0 100g
S17: …. I did 200 grams minus 100 grams because I am doing limiting reagents. Then I found the molar mass…
I: So, which one is the limiting reagent?
S17: Hydrazine.

Although Amelia found the right LR luckily and accidentally using faulty reasoning but interestingly she did not use it in the rest of the solution. Instead, she solved the problem using the amount of N_2O_4. It looked that she did not really know the function of the LR. Vanessa (S16) also used similar reasoning and chose the one with less mass but followed a very different path.

$$100gN_2H_4 \times \frac{1molN_2O_4}{2molN_2H_4} = 50gN_2O_4$$

$$2N_2H_4 + N_2O_4 \rightarrow 3N_2 + 4H_2O \qquad 200gN_2O_4 \times \frac{2molN_2H_4}{1molN_2O_4} = 400gN_2H_4$$

S16: Actually, the limiting reactant, I cannot remember the formula to find the limiting reactants. 100 grams of N_2H_4 times 1 and 204 N_2H_4 equals 50.0 gram N_2O_4 and then we have 50.0 N_2O_4 times 1 and 204…why am I doing this, what am I doing with this, why I am missing this because I am still going to end up back where I started from. 1 and 204 over 2 N_2H_4 equals, I am still going to end up with 100. I just went backwards. This would be 200. Why am I doing that? (Doing calculations)…no I am messing myself up with this…(doing more calculations)…400.0 grams of N_2O_4. So the limiting reactant would be here.

I: N_2O_4?
S16: N_2O_4.
I: How do you know that?
S16: Because I took the 100 grams of the N_2H_4 multiplied it by 1 N_2O_4 over 2 N_2H_4 and then I took the 200 grams of N_2O_4, multiplied it by 2 N_2H_4 over 1 N_2O_4 and it gave me 400 grams of N_2O_4. This should be N_2H_4. No because I am crossing those out, this is N_2O_4 and this is N_2H_4.
I: So, the limiting reactant is…
S16: The limiting reactant would be the N_2O_4.
I: Because its mass is less…
S16: Right.

One thing really caught my attention in Vanessa's solution was her high self-confidence. Although she completely followed an incorrect method from the beginning to the end, she did not feel hesitant about the trueness of her method. It reminded me the fact that some students might have shown insistence in doing wrong things. Moreover, they could not learn the right method until they realized that they were doing the pieces incorrectly.

Summary of the LR and Knowledge in Pieces. The average success rate of the LR piece indicated that students were good at LR piece once they knew that they needed to determine the LR. Besides the students who determined the LR incorrectly, there were students, who found the LR correctly, after they were reminded to consider the LR. Six students got the right LR, in the question eight, after they received the hint. It was an important sign showing that knowledge was in pieces and pieces existed in students' minds but students could not always retrieve those knowledge pieces or could not think of the types of the pieces needed in the questions although they had solved

similar problems many times before. It was very similar to the situation in which students could not explain correctly why summers are hot and winters are cold although they knew that earth has a tilt. However, when they were reminded this piece of knowledge, they suddenly start making a better and, maybe, right explanation about formation of the seasons. These examples showed that the sources of the students' poor performances were not always related to students' misconceptions or poor understanding of the pieces. There were also the cases where the problem was students' inability to retrieve the pieces and put them together successfully although the pieces did exist in their minds.

Mole Concept (MC)

What the Mole Concept is. A mole simply represents Avogadro's number (6.023×10^{23}) of objects – usually atoms or molecules. Converting between moles and grams of a substance is often important. This conversion can be easily done when the atomic and/or molecular weights of the substance(s) are known. Given the atomic or molecular weight of a substance, that mass in grams makes a mole of the substance. For example, calcium has an atomic weight of 40 atomic mass units. So, 40 grams of calcium make one mole, 80 grams make two moles, etc.

The Role and Function of the Mole Concept. One of the topics which students find difficult to understand is the mole concept. Although the mole

concept is not the most difficult one to understand in introductory chemistry, its mastery is essential to use chemical reasoning (Kolb, 1978). The importance of the topic is supported by the existence of abundant research into the problem of the teaching-learning of the mole concept in the last decades (Duncan & Johnstone, 1973; Furio *et al.*, 2002; Furio & Guisasola, 2000; Krishnan, 1994; Larson, 1997). Kolb (1978) stated that "there is probably no concept in the entire first year chemistry course more important for students to understand than the mole and one of the main reasons the mole concept is so essential in the study of chemistry is stoichiometry." Our non-parametric analysis also revealed that there is a significant correlation ($r=..91$, $p<0.01$) between the achievement in mole concept and the success with the problem solving in stoichiometry.

Overall Performance on the MC. The analysis also revealed that students in general are very good at doing the mole concept (MC) piece. They got a success rate of 95% overall. Except one student, all students got a score of 83% or above. This piece was used 620 times in total. Six students did not do any mistake at all while six students did make just one mistake with this piece and received a score of 98% or higher. Vanessa (S16) had the poorest score from this piece and appeared to have the poor understanding of the of the MC piece.

Table 4.9
Subjects' Performance with the Mole Concept Piece

SBJ	MC									
	95%									
	NR	CD	UDI	DD	DSE	URH	UG	**S**	**T**	%
	65	3	27	122	22	0	4	**590**	**620**	
01	0	0	1	3	1	0	0	44	45	**98%**
02	2	0	1	6	1	0	1	38	39	**97%**
03	6	0	0	3	1	0	0	39	39	**100%**
04	0	1	3	8	1	0	0	36	40	**90%**
06	5	0	3	8	1	0	0	32	35	**91%**
07	3	0	1	3	0	0	0	42	43	**98%**
08	3	0	1	10	2	0	0	33	34	**97%**
09	6	1	0	5	2	0	0	35	36	**97%**
10	2	1	0	3	0	0	0	43	44	**98%**
11	3	0	0	3	0	0	0	43	43	**100%**
12	8	0	0	5	1	0	0	35	35	**100%**
13	4	0	1	14	2	0	0	28	29	**97%**
14	5	0	0	3	1	0	0	40	40	**100%**
15	7	0	2	9	2	0	0	29	31	**94%**
16	5	0	8	24	5	0	2	5	13	**38%**
17	5	0	5	11	2	0	1	25	30	**83%**
18	1	0	1	4	0	0	0	43	44	**98%**

Typical Difficulties and Mistakes with the MC. Students did make mistakes occasionally with MC piece and the reasons appeared to be that either they were not careful enough or had some misunderstandings about the MC piece. Although those mistakes were not very common, they still deserved a special attention because there was a possibility of seeing them more often in a larger population. The difficulties and mistakes included:

- Mistakes about the mass and the molar mass in the formula of the MC

- Incorrect use of MC formula
- Misuse of the subscripts in calculation of the molar mass and the MC

Mistakes about the Mass and Molar Mass in the Formula of MC. Although Tammy (S04) used the formula of the MC correctly, she, in Problem 1, did use the mass percent of water as the mass of the water to calculate the number of moles of the water. Moreover, it appeared that she was not careful with using the units. Her partial solution was as follows:

$$n_{H_2O} = \frac{.108 H_2O}{18.0 g H_2O} = 6.00 \times 10^{-3} mol$$

Vanessa (S16) also followed another very unusual method to find the number of moles of water in Problem 1. She divided the mass of whole hydrate by the molar mass water.

$$n_{H_2O} = \frac{499.52 g/mol}{18.0 g/mol} = 27.8 g/mol$$

She did not only follow incorrect method to find the number of moles but also made a mistake with the unit of moles. She was not sure what those number and unit represent because of the poor understanding of the mole concept. I tried to understand if she was aware that the figure she reported meant that water's molar mass was 27.75g.

> S16: Determine x in narceine…x would equal 18 grams per mole of H_2O and then to find it out (doing calculations)…27.75 grams per mole.
> I: What is this number you found?
> S16: 27.75 grams per mole of H_2O in narceine.
> I: Do you mean that water has 27.75 grams per mole?
> S16: Right, the water is 27.75.

> I: Is that the molar mass of water?
> S16: The molar mass of water is 18. If the molar mass of narceine hydrate is 499.52 grams per mole determine x in narceine. When I'm looking at this, what I am seeing is determine how many waters are in narceine, but then it is saying that it's…

She first could not understand what I was trying to find out and told that water has 27.75g per mole. When I explicitly used the term, molar mass, she immediately remembered the value for the molar mass of the water and rejected the 27.75g to be the molar mass of the water but could not see her own mistake and could not realize that the unit "g/mol" represents the molar mass of a substance. She had apparently poor knowledge of the units as well.

Moreover, she had poor understanding of the meaning of the mass and the particle nature of matter. She did not know that each particle (atom) has a different mass and the mass of a molecule is the sum of the mass of the atoms in the structure. In Problem 3, she used the mass of CO_2 as both the mass of C and the mass of O_2 and calculated their numbers of moles. In the same manner, she did calculate the numbers of moles of H and O using the mass of H_2O as the mass of H_2 and the mass of O as follows:

$$m_{H_2O} = 1.089g \qquad m_{CO_2} = 2.657g$$

$$n_{H_2} = 1.089g \times \frac{1mol}{2g} = .544 \qquad n_C = 2.657g \times \frac{1mol}{12g} = .221$$

$$n_O = 1.089g \times \frac{1mol}{16g} = .068 \qquad n_{O_2} = 2.657g \times \frac{1mol}{32g} = .083$$

Vanessa did not know what she was really doing. She did not have the MC piece and was *lacking of proper understanding of the units*. She, in Problem

1, did use the "g/mol" as the unit of the number of moles. Another student, who had the problem with the units and the MC piece, was Amelia (S17).

Incorrect Use of the Formula of the MC. Amelia, in Problem 3, did divide the molar masses of hydrogen and the oxygen by their masses to find their numbers of moles:

$$n_{H_2} = \frac{2}{1.089} \qquad n_{O_2} = \frac{16}{1.089}$$

Amelia, as different from Vanessa, did not use the units at all for any number plugged into the formula in Problem 3. In another question, however, she used the units correctly but again made a mistake regarding the use of the formula. She multiplied the molar mass of carbon by its mass to obtain the number of moles of the carbon.

$$m_C = .351g$$
$$12.01g/mol = \frac{n}{.351g}$$
$$n_C = 4.22mol$$

It was clear that she had issues with the MC piece and the use of formula to calculate the number of moles. Faith (S15) also made a mistake while using the formula. She, in Problem 8, used the formula of the mole incorrectly.

$$m_M = m_{M_6I_2} - m_I = 102.58g - 55.81g = 46.77g$$
$$n_M = 1.32mol$$
$$MM_M = 1.32mol \times 46.77g = 61.7g/mol$$

She multiplied the number of moles of M by its mass to get the molar mass of the M in the formula of M_6I_2. It was obvious that Faith also had poor understanding of the MC.

Other mistakes made by the students were also regarding either the formula or the components of the formula. For example, Jason (S02), in Problem 8, did use an unusual formula. He divided the Avogadro's number (number of particles per mole) by the mass of M found in the formula of M_6I_2 to get the number of particles in the 46.77 g of M. He used the units and the formula incorrectly. It looked that he knew little bit about everything but could not put them together. He did have a great difficulty with connecting the micro world to the macro one and failed.

$$m_M = 46.77g$$
$$46.77g = \frac{6.02\times10^{23}amu}{X}$$
$$X = \frac{6.02\times10^{23}}{46.77} = 1.29\times10^{22}amu$$

Misuse of subscripts in the Calculation of the Molar Mass and the MC.

In the same problem, Guillermo's solution revealed another difficulty and a mistake regarding the mole concept. Guillermo (S06) tried to find the number of moles of I in M_6I_2 using an incorrect method. He had multiplied the molar mass of iodine by two since iodine had two as subscript in the formula of M_6I_2 before he calculated the number of moles of I.

$$m_I = 55.81g$$
$$MM_{I(M_6I_2)} = 2 \times 127 = 254g/mol$$
$$n_I = \frac{55.81g}{254g/mol} = .220mol$$

Although other students in the study did not make the same mistake, I have detected from the classes I have taught that this has been a common misunderstanding about the meaning of the molar mass and subscripts among the freshman students. They do not realize that subscripts are not constant and elements might have different subscripts in different compounds. The element molar masses have to be the same and constant because atoms have specific masses and the certain number of those atoms has always the same mass. If we change the value of molar masses of the elements, we implicitly say that the same mass of the element contain different number of atoms in different compounds, which we know, is impossible.

Summary of the MC. As is seen in the analysis, there were relatively few issues and mistakes related to the MC piece. Each mistake was observed once or twice in different students' solutions, except the one, which was again regarding the molar mass. We determined that many students had issues with the meaning of molar mass and, naturally, with the mole concept and the particle nature of matter. The students were adding the molar masses of the different compounds found in the mixtures and using the result as the molar mass of the mixture when they did not know how to solve the

problems. Vanessa (S16) in Problem 4, Silas (S01), Tammy (S04), and Yang (S18) in Problem 9 did this operation and treated the new number as the molar mass (MM) of the mixture and used it to calculate the number of moles of the mixture.

$$m_{ore(V_3S_4 \oplus V_5S_4)} = 10.5g$$

$$\left.\begin{array}{l} MM_{V_3S_4} = 280.7g/mol \\ MM_{V_5S_4} = 382.5g/mol \end{array}\right\} \quad MM_{(V_3S_4 \oplus V_5S_4)} = 663.2g/mol$$

$$n_{ore} = \frac{10.5g}{663.2g/mol} = .0158mol$$

These operations were problematic although what they did made sense to them. They were not aware that adding the molar masses meant that they were implicitly changing the molecular formula of the compounds and making a new compound. We know that we cannot easily add two different compounds arbitrarily. This requires a reaction, which depends on the types of the compounds and the conditions where the reaction is occurring.

Overall, with success rate of 95%, we can say that the students had MC piece at very high level.

Stoichiometric Ratio (SR)

What the SR is and its Function. There is no doubt that stoichiometric ratio (SR) is one of the fundamental pieces for the problem solving in stoichiometry but it can only be used when the equation is balanced and the

number of moles are found. The analysis revealed that these facts were not known or understood well by the students.

Overall Performance on the SR. Let us consider the following example. The amounts of sulfuric acid were given in different units and other substances' amounts were asked.

$$H_2SO_4 + 2KOH \rightarrow K_2SO_4 + 2H_2O$$

H_2SO_4 (98g/mol) given	*KOH (56g/mol) required*	*K_2SO_4 (174g/mol) produced*	*H_2O (18g/mol) produced*
49g of sulfuric acid	….g of KOH (56g)	….g *of K_2SO_4* (87g)	….g of *H_2O* (18g)
3.01×10^{23} molecules of sulfuric acid	….molecules of KOH (6.02×10^{23})	….molecules of K_2SO_4 (3.01×10^{23})	….molecules of H_2O (6.02×10^{23})
196g of sulfuric acid	….molecules of KOH (24.08×10^{23})	….g of *K_2SO_4* (348g)	….mol of *H_2O* (4mol)

Some of the successful students (seven of them) did actually show that type of the reasoning and the fluency and got a success rate of 93% or above with one UGI or CD or both codes. Most of the students did well with the SR pieces. Only six students got a success rate below 80% but above 67%. The SR piece in all the problems, 278 times appeared and 240 times were done successfully by the students. We also noticed that, in the analysis of this piece, we used

the code, DD, 69 times, which was greater than any other pieces except the MC piece.

Table 4.10
Subjects' Performance with the Stoichiometric Ratio Piece

SBJ	SR									
	86%									
	NR	CD	UDI	DD	DSE	URH	UG	**S**	**T**	%
	56	3	35	69	5	0	0	**240**	**278**	
01	3	0	5	6	0	0	0	10	15	**67%**
02	3	0	4	5	0	0	0	12	16	**75%**
03	4	0	1	1	0	0	0	18	19	**95%**
04	4	1	3	3	0	0	0	13	17	**76%**
06	3	0	4	7	0	0	0	10	14	**71%**
07	3	0	3	3	0	0	0	15	18	**83%**
08	4	0	1	5	1	0	0	13	14	**93%**
09	3	0	1	4	0	0	0	16	17	**94%**
10	1	0	1	0	0	0	0	22	23	**96%**
11	3	1	0	0	0	0	0	20	21	**95%**
12	4	0	2	1	0	0	0	17	19	**89%**
13	4	0	2	9	1	0	0	8	10	**80%**
14	4	0	2	2	0	0	0	16	18	**89%**
15	3	0	1	4	0	0	0	16	17	**94%**
16	5	0	1	13	3	0	0	2	3	**67%**
17	2	0	4	6	0	0	0	12	16	**75%**
18	3	1	0	0	0	0	0	20	21	**95%**

However, when we take the percentage of the number of DDs to the whole number of the pieces required in the questions for each piece, we found that percentage of DDs was the third highest in the SR piece among all the pieces. The other two pieces had the highest percentage of DDs were LR and PY pieces. Since the SR piece was not the goal in the solutions but more like a

tool to reach the goal and students did not see their goals clearly, so they could not always see the necessity of the SR piece. Therefore, the percentage of DDs in the SR piece appeared greater than that of DDs in other pieces.

Typical Difficulties and Mistakes with the SR. The analysis helped us to see the mistakes related to the use of the SR piece:

- Use of the molar mass instead of the number of moles in establishing the stoichiometric ratio
- Setting up the SR incorrectly
- Misuse of the coefficients along with the mass in setting the SR
- Incorrect use of the subscripts in setting up the SR
- Use of the mass percent in setting up the SR

Incorrect Use of Molar Mass in Establishing the SR. Guillermo's (S06) solution of Exercise 13 is an example of how students sometimes use molar mass without finding the number of moles:

$$Cu_2S + 3/2O_2 \rightarrow Cu_2O + SO_2$$

$$\frac{159gCu_2S}{1\cancel{molCu_2S}} \times \frac{1\cancel{molCu_2S}}{1molSO_2} = 159g/molSO_2$$

$$m_{SO_2} = 10mol \times 159g/mol = 1,590gSO_2$$

In his solution, unfortunately, the mistakes were not limited to the ones related to the SR piece. He also made mistakes with units and the MC piece by accepting the molar mass of Cu_2S as the molar mass of the SO_2.

Setting up the SR Incorrectly. For Exercise 13, Gwen (S13), used the right quantities in the equation, but set the ratio up incorrectly. She was not aware that if she set up the ratio that way the unit of the answer could not be "mol". It, on the contrary, would be "mol²/g", which indicated to her that she was making a mistake.

$$4Cu_2S + 6O_2 \rightarrow 4Cu_2O + 4SO_2$$

$$10molCu_2S \times \frac{1mol}{159g} \times \frac{6molO_2}{4molCu_2S} = .0943molO_2$$

Because Gwen realized her mistake, she was able to correct it.

$$10molCu_2S \times \frac{4molSO_2}{4molCu_2S} \times \frac{64.07gSO_2}{1molSO_2} = 640.7gSO_2$$

Since the SR piece was used as a tool to reach the other pieces, we did not want to exclude the rest of the solutions in our analysis. Rather, we preferred to share the mistakes and details related to other pieces as well while talking about the students' performance with the SR piece.

Misuse of Coefficients along with the Mass in Setting up the SR. Among all the students, Vanessa (S16) and Silas (S01) showed the poorest performance with the SR piece. The reasons behind their poor performance might be due to their misunderstandings about the meaning of the SR piece and the function of the coefficients in the equations. Vanessa, in Exercise 8, made a fundamental mistake and set up the ratio using the mass instead of

the number of moles, which revealed her misunderstanding about the SR piece. In addition, she did use the wrong coefficient for SiC:

$$SiO_2 + 3C \rightarrow SiC + 2CO$$

$$100.0kgSiO_2 \times \frac{2SiC}{1SiO_2} = 200kgSiC$$

She did not apparently know that coefficients in the equations could only be used with the number of moles. Like Vanessa, Silas, in Problem 10, attempted to establish a ratio involved the consecutive reactions. However, he failed in finding the right ratio and used the coefficients incorrectly because he did not consider intermediate steps.

$$Cl_2 + 2KOH \rightarrow KCl + KClO + H_2O$$

$$3KClO \rightarrow 2KCl + KClO_3$$

$$4KClO_3 \rightarrow 3KClO_4 + KCl$$

Silas here went from the amount of the $KClO_4$ to the number of moles of Cl_2 directly and just used the first and final steps in the reaction sequence. He took the coefficient of $KClO_4$ from the final step and the coefficient of the Cl_2 from the first step and set up the equation.

$$1.44molKClO_4 \times \frac{1molCl_2}{3molKClO_4} = .48molCl_2$$

On the other hand, Guillermo in the same problem added the coefficients coming from the different steps and made a similar mistake as Silas did:

$$1.44molKClO_4 \times \frac{7molCl_2}{1molKClO_4} = 10.1molCl_2$$

Neither of the methods were correct because the coefficients can only tell the ratio in the same equation. Both Silas and Guillermo did not know that there were two things they could do to solve the problems involving the reactions occurring in more than one step, using the mass conservation principle and carefully transfer the amount of the substances from one step to the following one or adding those steps and getting one net equation after multiplying or dividing with proper numbers and doing necessary cancellations.

Unfortunately, the incorrect use of coefficients was not limited to Silas and Guillermo. It was a common mistake; especially in the problems containing the reactions have multiple steps. For example, in Problem 9, several students (Jason (S02), Lady (S08), Steve (S12), Bob (S14), and Amelia (S17)) used the coefficients incorrectly. Problem 9 included two reactions occurring simultaneously:

$$V_3S_4 + 4O_2 \rightarrow 4SO_2 + 3V$$

$$V_5S_4 + 4O_2 \rightarrow 4SO_2 + 5V$$

The students were required to find the amount of the V_3S_4 in the mixture using the amount of total V produced by both reactions. All of the students calculated the number of moles of V correctly, but they made mistakes regarding the SR piece and other pieces. Students did the following calculations to find the amount of V produced by each reaction.

$$n_V = .128mol$$
$$n_{V(V_3S_4)} = .128mol \times \frac{3}{8} = .0480mol$$
$$n_{V(V_5S_4)} = .128mol \times \frac{5}{8} = .0800mol$$

The solutions illuminated one of the students' common misunderstandings about the roles of coefficients and showed that how this misunderstanding caused them to make other mistakes while they were solving the problems.

Incorrect Use of Subscripts in Setting the SR. The mistakes mentioned above were not done only while dealing the two reactions or with reactions happening at multiple steps but also while dealing with individual molecules since students did not have a good understanding of the function of the subscripts. Silas (S01) and Aubrey (S07), in Problem 6 found the number of moles of C in CH_4 and C_2H_6 by setting the equation as follows:

$$2.5molCH_4 \times \frac{1Catom}{5atoms} = .50molC$$
$$2molC_2H_6 \times \frac{2Catoms}{8atoms} = .50molC$$

Their calculation revealed that in addition to having poor knowledge of SR piece, they had also poor understanding of the roles of the subscripts in the chemical formulas.

Use of Mass Percent in Setting the SR. In Problem 6, Bob (S14) made another unusual mistake and established a ratio between the mass percent and number of molecules.

40% Methane → 4 Methane molecules

60% Ethane →6 Ethane molecules

He was not fully aware that the percentages were showing how much we had from each of the compound in the mixture not particles although they were related to each other not in the way he used. Therefore, he failed and used the mass percent directly to find out the number of molecules without knowing the molar masses of the compounds, in other words, molecular weights.

Summary of the SR. The performance with the SR piece was directly affected by students' performance with and understanding of the other pieces. We observed that any misunderstanding with the roles of the coefficients in the equations and the subscripts in the chemical formulas misled the students and caused them to establish incorrect ratios. We found out that poor understanding of the units or molar mass resulted in poor performance with the SR piece. We learned that there was a complex interaction among the different pieces. Although it was difficult to explain this complicated interaction, we knew that it was almost impossible to separate the pieces from each other and study them individually. Therefore, in this study we examined all the pieces before drawing any conclusions about the students' problem solving performances in stoichiometry.

With the analysis of the SR piece, we actually finished the analysis of the pieces required for the solutions of the most common stoichiometry problems. However, we also wanted to see how students' ability and

knowledge to deal with the ratios would change as we changed the context and types of the questions. Therefore, in think-aloud protocols, we used two extra questions about the mathematical ratios. Results indicated that there were differences between the students' performance with the SR and MR pieces although the difference was not huge.

Extra Piece-Mathematical Ratio (MR)

The Difference between the Success Rates of the SR and MR. The analysis indicated that students were more successful with the MR piece than they were with the SR piece. They got a success rate of 94% from the MR piece while they had gotten a success rate of 86% with the SR piece. However, we had to keep in mind that MR piece was required just 34 times in total while students needed to do SR piece 278 times. Although statistical tests indicated that the difference between the students' success with the MR and SR pieces is significant ($p<.05$), we are hesitant to draw conclusions based on these scores since the number of the MR pieces done by students was not significantly a large number. Yet, we thought it might still show some signs about the students' ability and knowledge to do MR piece.

We tried to bring an explanation based on our observations, which might illuminate the difference. Students when they saw the mathematics questions, they suddenly felt comfortable and started to solve the questions. Although students did not explicitly told that those questions were easy or

different from the other questions, the success rate for MR pieces was showing that MR questions were easier for our students. Besides, those who did not share their opinions explicitly, there were a few students, who clearly expressed that they did notice the difference of these questions, which were easier to solve for them. Silas (S01) told, "*I know I can probably use all the concepts that I have learned in chemistry to solve this equation because it is just ratios*". Moreover, they were more confident with their solutions because they were able to decide if their solutions were making more sense to them or not. You can see this confidence in their transcripts. I extracted another portion from Silas transcript to show this confidence, "*I think...that makes sense...I have three of them...and one meter equals that...and that is how many feet I will have...*" Brooklyn (S03), on the other hand, easily found out that the answer did not make sense to her, "*...that is only one chair that cannot be right...unless you want...1.77 so that could only be one chair...but that does not seem right to me...*"

It was easy to understand why they felt more comfortable while solving the mathematics questions and explain why they easily detected their mistakes and corrected them when we looked at the differences between the mathematics and chemistry questions. The nature of the mathematics questions was different from the nature of the chemistry questions. The chemistry questions mostly required students to think at different levels, especially at micro level and connect it to the macro and symbolic levels while

the mathematics questions were more straightforward and did not require the students to use the abstract concepts such as the mole concept as the chemistry questions do. Moreover, the mathematics questions were very similar to the problems they encountered during their everyday lives. Therefore, they did not feel confused or struggle a lot and showed better performance with the mathematics questions and MR piece than they did with the chemistry questions and SR piece.

Some Details about the MR. The analysis of the MR piece was much simpler because we did not need to use other codes other than the UDI and S. Except two students, they all had the a success rate of 100%. Therefore, we did not have the difficulties or mistakes to talk about the MR piece other than a few interesting points I noticed in students' solutions. One interesting thing in the students' solutions regarding the MR piece caught my attention was that most students converted the units into English system to work further while just three students preferred to convert the units into the SI system.

The other point was about the common difficulty students had with the conversion of the units. Students were usually good at converting the units of length (cm to inch or vice versa) but they had a hard time while converting the units of the area (from cm^2 to ft^2 or vice versa). Some of the students drew the pictures to overcome of that difficulty. Jason (S02) and Yang (S18) were among those students and they benefited from their drawings and did the

conversions correctly. Other than these two points, we did not find any other important details about the MR piece in the analysis of the data to share.

Table 4.11
Subjects' Performance with the Mathematical Ratio Piece

SBJ	MR									
	94%									
	NR	CD	UDI	DD	DSE	URH	UG	**S**	**T**	%
	0	0	2	0	0	0	0	**32**	**34**	
01	0	0	0	0	0	0	0	2	2	**100%**
02	0	0	0	0	0	0	0	2	2	**100%**
03	0	0	0	0	0	0	0	2	2	**100%**
04	0	0	0	0	0	0	0	2	2	**100%**
06	0	0	0	0	0	0	0	2	2	**100%**
07	0	0	0	0	0	0	0	2	2	**100%**
08	0	0	0	0	0	0	0	2	2	**100%**
09	0	0	0	0	0	0	0	2	2	**100%**
10	0	0	0	0	0	0	0	2	2	**100%**
11	0	0	0	0	0	0	0	2	2	**100%**
12	0	0	0	0	0	0	0	2	2	**100%**
13	0	0	0	0	0	0	0	2	2	**100%**
14	0	0	0	0	0	0	0	2	2	**100%**
15	0	0	0	0	0	0	0	2	2	**100%**
16	0	0	1	0	0	0	0	1	2	**50%**
17	0	0	0	0	0	0	0	2	2	**100%**
18	0	0	1	0	0	0	0	1	2	**50%**

Conclusion

The analysis so far showed that students, except the EF and PY pieces, overall had a good understanding of the pieces necessary for the stoichiometric problem solutions although students occasionally had

difficulties with pieces and made mistakes while finding them. Table 4.12 shows that all the success rates that students got from each piece, which were investigated throughout all the questions used in the study.

We believe that these scores are quite convincing that the students were good at doing the pieces. By this information, we could partially answer the first research question and could say that the difficulty with solving the stoichiometry problems did not stem from the poor understanding of the pieces.

Table 4.12
The Students' Attempt Success Rates with all the Pieces

PIECES	ASR (%)
WRITING THE EQUATIONS -WEQ	45, 88(After Hint)
BALANCING THE EQUATIONS-BEQ	90
MASS PERCENT-MP	87
EMPIRICAL FORMULA-EF	54
MOLECLAR FORMULA-MF	88
PERCENT YIELD-PY	68
LIMITING REAGENT-LR	80
MOLE CONCEPT-MC	95
STROICHIOMETRIC RATIO-SR	86

Investigating the Total Success Rates in the Questions: Linking or Pieces or Something Else?

Now we turn to the second part of the question. To what extent does students' difficulty with stoichiometry stem from inability to link the pieces. We were aware that answering the second part of the question was much more difficult than answering the first part of the question.

Our further analysis hinges on the importance of question complexity, i.e. if difficulty does not stem from the pieces themselves then it might stem from the context that the pieces are in. With more complex questions, even simple pieces might become stumbling blocks because they are in a context that makes them challenging.

We again turn to consider the questions used in the study. There were twenty-five questions excluding the two math ratio questions. In the rest of the questions, there were twelve complicated questions, which can be called problems (P) and 13 simple questions, which can be called exercises (E) for our students in the study. The complex questions were different from the simple questions in a few ways. The complex questions usually had more types of the pieces, more number of pieces in total, and more conceptual steps. The solutions of the problems were not generally straightforward and required more than simple retrieval of the pieces and applying basic algorithm. Moreover, the problems required students to reconstruct the

information given in the problem, analyze it, and benefit from several methods to link the different numbers and types of the pieces to reach an answer.

As a part of the analysis of the questions, first we coded the pieces involved in the questions using the same codes we used for coding the pieces and calculated the success rates of the questions. As we mentioned before, we calculated the success rates of the pieces as *Attempt Success Rate* (ASR) which excluded the codes DD, DSE, and NR. We did not include those codes in our formula to calculate the success rates of students with the pieces because we were not able to say that students were either successful or not with that specific piece if they had not done that piece at all. To deal with difficulties associated with the context that varies with question complexity, we introduce new formula for the *Total Success Rate* (TSR):

$$TSR = \frac{S}{T(S + UDI + URH + UG + CD + DD + DSE)} \times 100 .$$

After finding the students' TSR for each question, we found out that the success rates of the questions were varied greatly, which can be seen clearly in Table 4.13. We, then, started to examine the possible factors on these varying scores to find out why students were more successful with exercises and some problems than others. Those factors are:

- Average Number of Pieces and Number of Piece Types
- Attempt Success Rates (ASR) of the pieces

- Schemas of the Questions along with
    - Contexts of the Questions (Contextual Factor) and Linking Ability
    - Codes Assigned to the Pieces in the Questions

Table 4.13
The Total Success Rates of the Students from the Problems

P&E	TSR (%)	T	S	NR	CD	UDI	DD	DSE	URH	UG
P1	82	34	28	0	1	5	0	0	0	0
P2	60	201	120	3	0	12	58	10	0	1
P3	50	101	50	1	2	9	33	2	5	0
P4	72	119	86	0	1	14	18	0	0	0
P5	63	90	57	12	0	1	13	2	17	0
P6	62	89	55	47	0	13	21	0	0	0
P7	94	85	80	0	0	2	3	0	0	0
P8	53	51	27	0	2	7	9	6	0	0
P9	44	123	54	47	4	28	19	0	16	2
P10	86	86	74	16	0	4	5	3	0	0
P11	72	102	73	0	2	6	18	1	0	2
P12	71	116	82	20	2	7	24	0	0	1
E1	65	34	22	0	0	12	0	0	0	0
E2	50	34	17	0	0	2	0	0	15	0
E3	85	34	29	0	0	0	0	0	5	0
E4	71	34	24	0	0	6	0	0	4	0
E5	97	34	33	0	0	1	0	0	0	0
E6	76	34	26	0	0	7	1	0	0	0
E7	89	47	42	4	1	4	0	0	0	0
E8	78	102	80	0	0	7	14	1	0	0
E9	87	119	104	0	0	6	6	0	2	1
E10	100	17	17	0	0	0	0	0	0	0
E11	94	34	32	0	0	0	0	2	0	0
E12	94	17	16	0	0	1	0	0	0	0
E13	76	85	65	0	0	3	2	0	15	0

We thought if we could find the factor or factors causing the variations in the total success rates, we would automatically have an answer for the first research question. Therefore, we focused on finding the sources of the differences and factors affecting on the differences in the total success rates.

Total Success Rates as a Function of the Average Number of Pieces and the Number of Piece Types

The first thing we noticed that the questions contained different total number of the pieces. Moreover, our further analysis revealed that the types of the pieces and their quantities of involved in the questions differed as well. The problem solvers had to deal with the different number and types of the pieces to solve the questions. Therefore, we thought that the total number of the pieces or the number of the piece types could explain the differences among the total success rates. We calculated the average numbers of the pieces required for each problem.

In order to find the average number of pieces, we divided total number of pieces required for each problem with the total number of students (17). For example, in Problem 2, students needed to use 201 pieces in total excluding the pieces that were not required for some students since they followed a different method from the one we used. We divided 201 by 17 and found the average number of pieces required for Problem 2 to be 11.8. The average numbers of pieces for the questions were varying from 1 to 11.8. Table 4.14

shows that there is no significant correlation, as evidenced graphically in Figures 4.1 and 4,2, between the total success rates and the average number of the pieces required for the questions or the number of the piece types involved in the questions.

Although we observed a better correlation between the total success rates and average number of pieces in the exercises than those in the problems, there were still variations in the total success rates, which were not proportionally increasing as the average number of pieces decreasing. There were many exercises with an average number of pieces of two but they had very different total success rates from 50 to 97. In the same manner, there were variations among the total success rates in the problems, which cannot be explained using the changes in the number of average number of pieces or the number of the piece types. In Problem 7, students got the highest score (94) among all the problems despite the four different types of the pieces and an average number of pieces of five. On the other hand, in Problem 8, total success rate (53) appeared to be one of the lowest success rates despite the low number of average number of pieces (3) and number of piece types (2).

We continued analyzing the influence of the average number of pieces and the number of the piece types on the total success rates by drawing the graphs, which were shown in Figures 4.1 and 4.2, and calculating the R^2 for each graph.

Table 4.14

The Ranking of the Questions Based on the Average Number of the Pieces

P&E	TSR (%)	Average Number of Pieces	Number of Piece Types	Types of Pieces
P2	60	11.8	4	LR & PY & SR & MC
P9	44	7.2	5	WEQ & BEQ & MC & SR & MP
P4	72	7	5	WEQ & BEQ & MC & SR & MP
E9	87	7	5	WEQ & BEQ & MC & LR & SR
P12	71	6.8	3	MC & SR & PY
P11	72	6	3	MP & MC & EF
E8	78	6	5	WEQ & BEQ & PY & MC & SR
P3	50	5.9	4	WEQ & MC & SR & EF
P5	63	5.3	4	WEQ & BEQ & MC & SR
P6	62	5.2	3	MP & MC & SR
P10	86	5.1	3	BEQ & MC & SR
P7	94	5	4	BEQ & MC & SR & PY
E13	76	5	4	WEQ & BEQ & MC & SR
P8	53	3	2	MC & SR
E7	89	2.8	3	MP & MC & MF
P1	82	2	2	MP & MC
E1	65	2	2	WEQ & BEQ
E2	50	2	2	WEQ & BEQ
E3	85	2	2	WEQ & BEQ
E4	71	2	2	WEQ & BEQ
E5	97	2	2	MP & MC
E6	76	2	2	MC & EF
E11	94	2	1	MC
E10	100	1	1	MC
E12	94	1	1	MC

We drew the graphs and calculated the R^2 because we wanted to make sure that there was not any significant interaction between the average number of

pieces and the number of the piece types and the total success rates, which could not be detected from the Table 4.14.

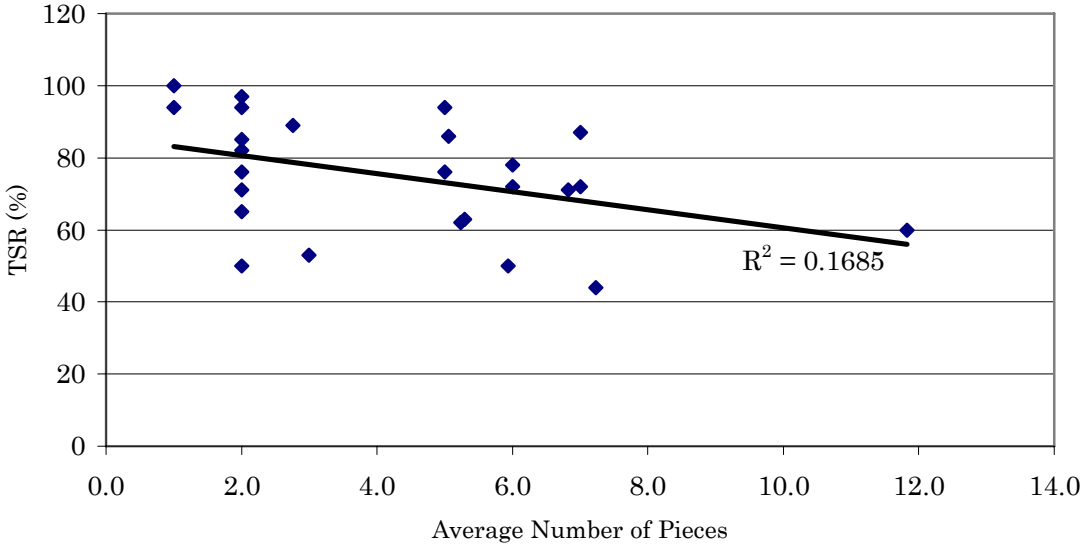


Figure 4.1: Total Success Rates as a Function of the Average Number of Pieces in both Problems and Exercises

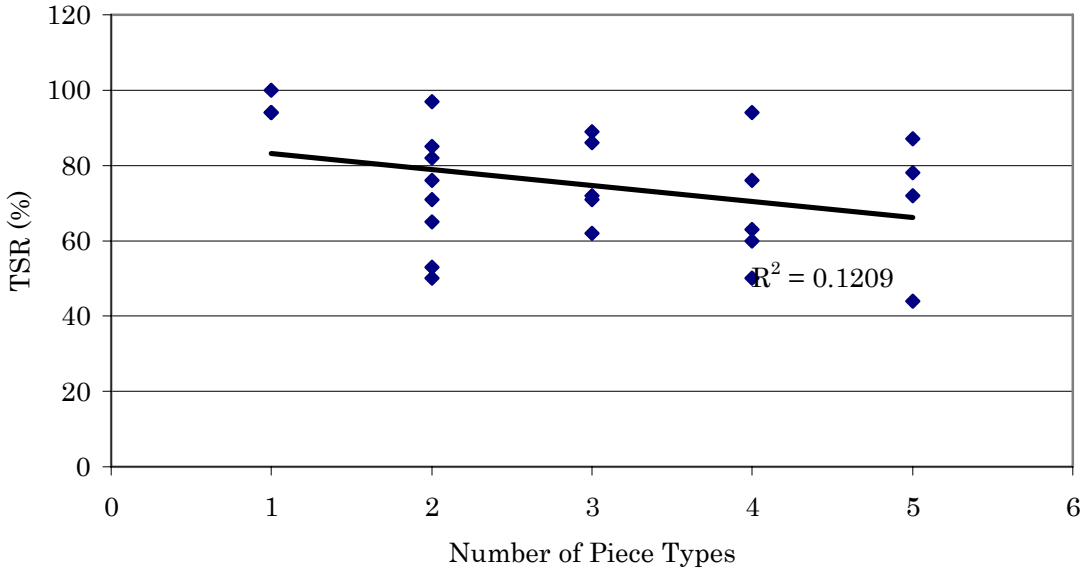


Figure 4.2: Total Success Rates as a Function of the Number of Piece Types in both Problems and Exercises

Both values of R^2 supported the Table 4.14 as well and showed no significant relationship between the total success rates of the questions and the average number of pieces and the number of piece types.

The Relation between Attempt Success Rates and the Variations in the Total Success Rates

In further analysis we considered carefully how the ASRs might be enough to predict TSRs. The pieces have the different success rates (ASR), which are depicted on the Table 4.12.

Table 4.15
The TSRs and the ASRs of the Pieces Involved in the Problems

P	TSR	ASR				
P1	82%	MP (87%)			MC (95%)	
P2	60%	LR (80%)	MC (95%)		SR (86%)	PY (68%)
P3	50%	WEQ (88%)	MC (95%)	SR (86%)	EF (54%)	
P4	72%	WEQ (88%)	MC (95%)	SR (86%)	BEQ (90%)	MP (87%)
P5	63%	WEQ (88%)	BEQ (90%)	MC (95%)	SR (86%)	
P6	62%	SR (86%)	MC (95%)		MP (87%)	
P7	94%	SR (86%)	MC (95%)	PY (68%)	BEQ (90%)	
P8	53%	SR (86%)			MC (95%)	
P9	44%	WEQ (88%)	MC (95%)	SR (86%)	BEQ (90%)	MP (87%)
P10	86%	SR (86%)	MC (95%)		BEQ (90%)	
P11	72%	MP (87%)	MC (95%)		EF (54%)	
P12	67%	SR (86%)	MC (95%)		PY (68%)	

The data on the Table 4.15 ,shows that ASRs *do not* serve as a good predictor for TSRs. For example, there are questions that have the same types of the pieces but different total success rates. For example, problem 4 and 9 have

the same types of the pieces (WEQ, BEQ, MC, SR, and MP) but they have a total success rate of 72 and 44, respectively. In the same manner, Exercises 1, 2, 3, and 4 have the same types of the pieces (WEQ and BEQ) but again they all have varying scores from 50 to 85.

We, unfortunately, after all examinations, found out that there was no strong relationship between the ASRs and TSRs in other words, students' performance on the pieces and in the problems. Having good success rates with the pieces did not always guarantee the higher success rates in the problems. So, if the success rates of the pieces did not account for the varying students' performance with the problems, what was the thing affecting the unstable success rates of the students?

The Influence of Schemas on the Variations in the Total Success Rates

We believe the varying TSRs can be partly understood by examining the schemas of the questions. A schema is a diagram that shows how the pieces in the problem are connected together. In our investigation of the questions, we found that they require different schemas for their solutions. In the problems, in which students showed poor performance, the way the the pieces connected to each other was more complicated than those in the problems in which students showed good performance.

To investigate the influence of the schemas necessary for solving the problems, we again chose two problems from the low group and two problems

from the high group. Low group problems were Problem 3 and 9 with the success rate of 50% and 44%, respectively, and high group problems were Problem 7 with the success rate of 94% and Problem 10 with the success rate of 86%.

When we examined the schema for Problems, 7 and 10 and the exercises where the students' achievements were high, we clearly saw that the schemas were simple and were straightforward. Of course, students still needed to be good at all the pieces to reach the final answer in these kinds of problems. The pieces in the problems were connected to each other like the little cogwheels in the clocks. If one of them broke down or missed, then getting the right answer would be too difficult or maybe impossible. Therefore, to explain the differences in the success rates in such problems, students' accomplishments with the pieces can be used.

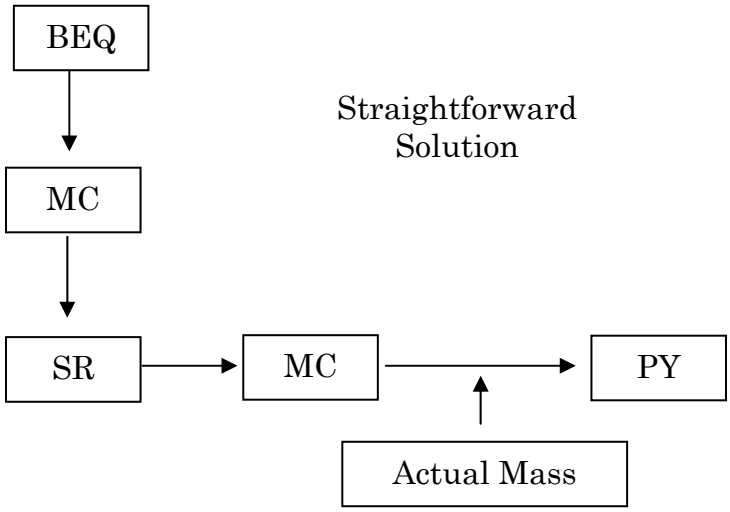


Figure 4.3: Schema for Solving the Problem 7

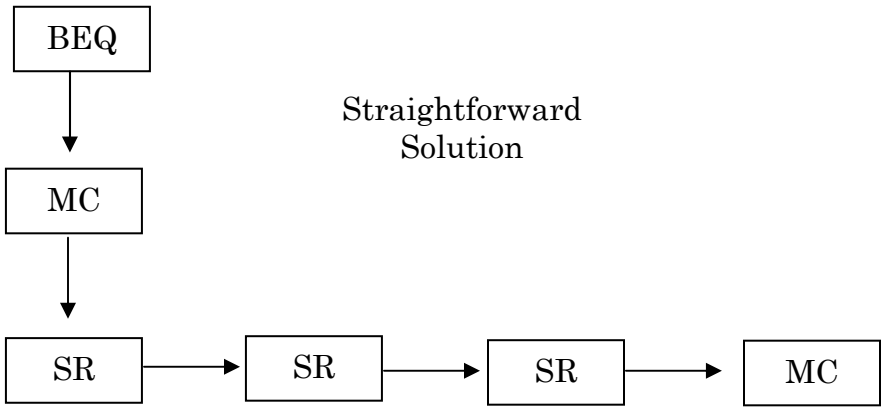


Figure 4.4: Schema for Solving Problem 10

On the other hand, with Problem 9 and 3 because being good with the pieces not necessarily guarantee the success because the pieces were arranged in a more complicated schema.

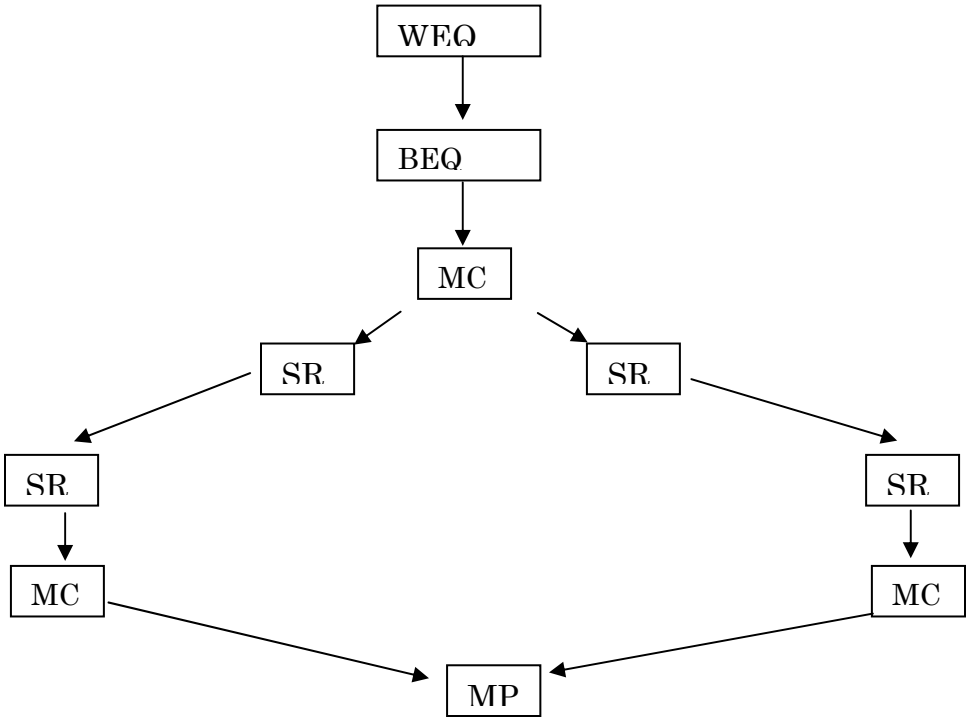


Figure 4.5: Schema for Solving Problem 9

The schema necessary for the solution of Problem 9 indicated that students could not get the right answer by just following simple steps as they did in Problem 7 or 10. They here first had to have a good knowledge of pieces, know how to put the pieces together, and finally decide and choose the most efficient method to solve the problem. In these kinds of the problems, the most common characteristics of the students was that they were explicitly telling that they did not have any clue how to do problems or they knew little bit from everything but could not link them successfully and made a lot of mistakes. As a result, students got many DDs or the UDIs from those problems.

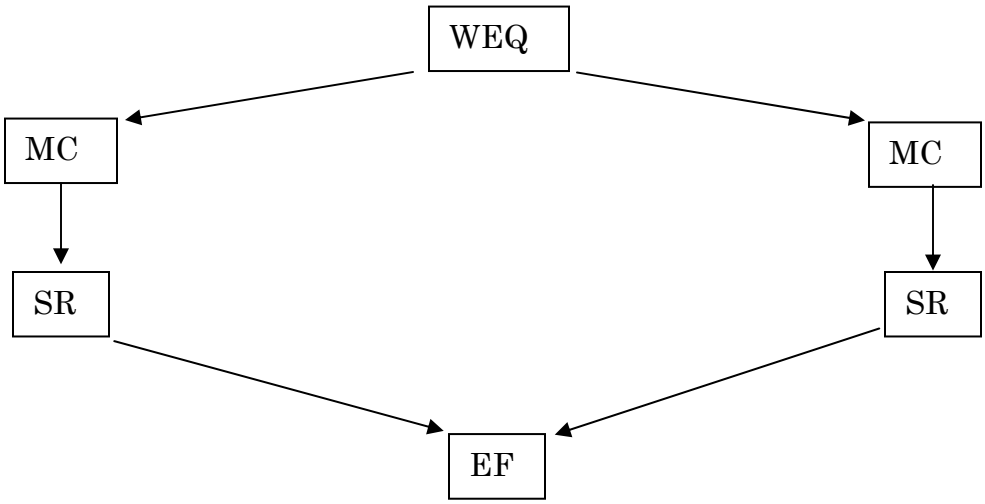


Figure 4.6: Schema for Solving Problem 3

For Problem 3 even though students knew how to balance an equation, calculate the number of moles, and had the ability to handle stoichiometric ratios in less complex contexts, they could not succeed here. They either

missed the steps or did them incorrectly. Apparently, being good with the pieces is not enough to be successful in solving all kinds of stoichiometry problems.

Examination of all the schemas of the problems in Table 4.17a and 4.17bb along with the TSRs reveals that the schemas of the questions can be used to explain the variations in the TSRs, in other words, students' performances. After unsuccessful attempts to find the sources of the differences among the TSRs using the average number of pieces, the number of piece types, ASRs of the pieces, it was nice to see a variable showing strong relation with the TSRs.

The schemas indeed provided good graphical information to explain total success rates, but we wondered if there was a simple quantitative way to represent this same information. For that purpose, we introduce below a new quantity, the *contextual factor.*

The Contextual Factors of the Questions and the Variations in Total Success Rates

To quantify how important the context or the "linking" is, we first consider the extreme hypothetical situation in which linking was completely *unimportant*. In this case, which we called the *Pieces Only Model*, solving a complex problem that involved several pieces would be no more difficult than solving several one-piece exercises that involved the same set of pieces. If the

Pieces Only Model were valid, then we should have been able to predict student success rates on complex problems based on the student success rates for individual pieces.

To test the validity of the Pieces Only Model, we considered again the Attempt Success Rate (ASR) for each piece as had been discussed previously:

$$ASR = \frac{S}{S + UDI + URH + UG + CD} \times 100\%,$$

where *ASR* is calculated for a given type of piece (e.g. mole concept (*MC*), balancing equation (*BEQ*), etc.) averaging over all students' attempts of the piece and all problems and exercises. Note that the *ASR* denominator *does not* include those instances where a subject did not know to do a particular piece (*DD*), did something else (*DSE*), or solved that problem in a way that did not require the piece (*NR*). In this way, the *ASR* is strictly a measure of how frequently our subjects were successful with a piece type *given that* the piece was attempted.

If the Pieces Only Model is valid, then the Total Success Rate (*TSR*) for a given problem should be an average of the Attempt Success Rates for the pieces included in the problem. Recall that:

$$TSR = \frac{S}{S + UDI + URH + UG + CD + DD + DSE} \times 100\%.$$

It is important to realize that TSR is distinct from ASR in a couple ways. *TSR*'s denominator includes *DD* and *DSE*. In this way, with the *TSR* students are considered *not* successful if they do not know to do a piece or

they do something else (unproductive) instead of the piece. The implication here is that if a student does not know that they should do a piece; this is a type of failure to "link" successfully. The *TSR* is also distinct from the *ASR* in that *TSR* is calculated on a *per problem* basis (averaging over all students and all pieces in the problem) and *ASR* is calculated on a *per piece type* basis (averaging over all students and all problems). To make this distinction explicit, we will include subscripts to indicate piece type (for *ASR*) and problem number (for *TSR*) in the following example.

Consider the following example prediction of the Pieces Only Model. Problem 1 contains two pieces: a mole concept (*MC*) piece and a mass percent (*MP*) piece. The *TSR* for Problem 1 is predicted by the Pieces Only Model to be:

$$TSR_{P1}^{POM} = \frac{ASR_{MC} + ASR_{MP}}{2},$$

where the superscript *POM* indicates that this is a Piece Only Model prediction. By considering the gap between the *POM* prediction and the true *TSR* for a given problem we can quantify how important *linking* and the context of the questions are for that problem. We will call this gap the contextual factor because we believe that the students' ability to link pieces together is determined by the context that the pieces are found in. See the Table 4.16 for a summary of *POM* predictions and contextual factors for each of the exercises and problems considered in this study.

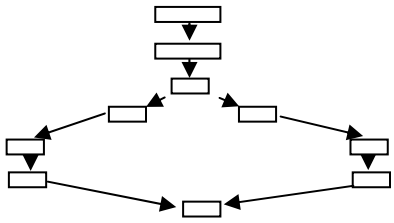
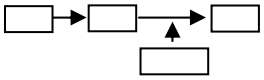
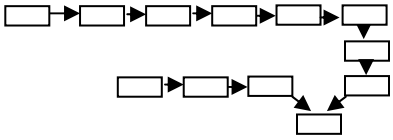
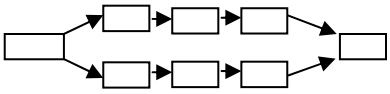
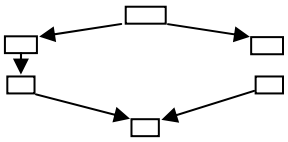
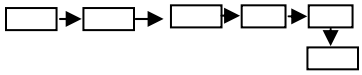
Table 4.16
Contextual Factors in the Questions

Q	Pieces Needed	TSR ^{POM} (%)	TSR ^{actual} (%)	Contextual Factor
P9	WEQ, BEQ, MC(3), SR(4), MP	85	44.0	41
P8	MC(2), SR	92	53.0	39
P2	LR, MC(7), SR(3), PY	89	60.0	29
P6	MC(4), MP(2), SR(2)	91	62.0	29
P3	WEQ, MC(2), SR(2), EF	77	50.0	27
P5	WEQ, BEQ, MC(2), SR(2)	83	63.0	20
E2	WEQ, BEQ	68	50.0	18
P12	MC(4), SR, PY(2)	86	71.0	15
P11	MP, MC(4), EF	87	72.0	15
P4	WEQ, BEQ, MC(3), MP, SR	85	72.0	13
P1	*MC, MP*	91	82.0	9
E13	WEQ, BEQ, SR(2), MC	80	76.0	4
P10	BEQ, MC(2), SR(3)	90	86.0	4
E1	WEQ, BEQ	68	65.0	3
E8	WEQ, BEQ, PY, MC(2), SR	80	78.0	2
E7	MP, MC, MF	90	89.0	1
E11	MC(2)	95	94.0	1
E12	MC	95	94.0	1
E6	MC, EF	75	76.0	-2
E9	WEQ, BEQ, MC(3), LR, SR	84	87.0	-3
E4	WEQ, BEQ	68	71.0	-4
E10	MC	95	100.0	-5
E5	MC, MP	91	97.0	-6
P7	BEQ, MC(2), SR, PY	87	94.0	-7
E3	WEQ, BEQ	68	85.0	-18

Contextual Factors, Schemas, and the Variations in the Total Success Rates

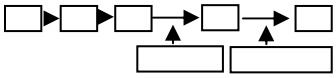
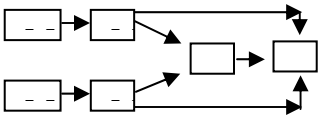
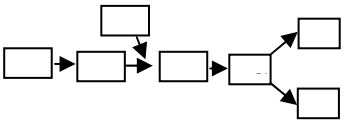
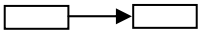
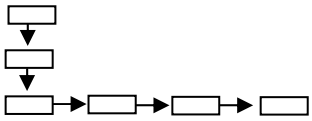
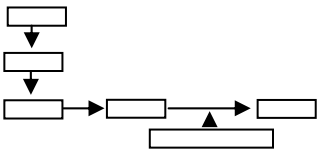
To see how the Contextual Factor is a useful proxy for schema complexity, we present them side by side in Tables 4.17a, 4.17b, and 4.18.

Table 4.17a
The Contextual Factors, Schemas, and the TSRs for Problems

P	CF	Schemas	TSR (%)
P9	41		44
P8	39		53
P2	29		60
P6	29		62
P3	27		50
P5	20		63

The data on the Table 4.17a (difficult problems) and 4.17b (easier problems) regarding revealed that despite the some variations there is a good harmony among the schemas of the problems and the contextual factors.

Table 4.17b
The Contextual Factors, Schemas, and the TSRs for Problems

P	CF	Schemas	TSR (%)
P12	15		71
P11	15		72
P4	13		72
P1	9		82
P10	4		86
P7	-7		94

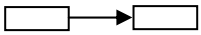
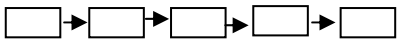
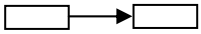
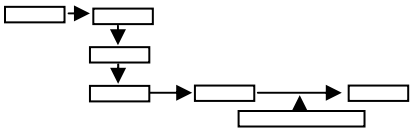
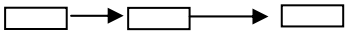
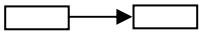
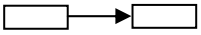
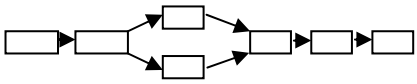
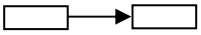
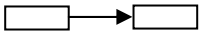
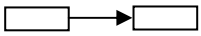
In the Table 4.18, which includes data about *exercises*, we do not see the same level of harmony among the schemas of the questions and the

contextual factors. Apparently, the system that we have developed (schema and the contextual factor) is better at differentiating between problems of various difficulty than between exercises of various difficulty.

To illustrate our findings, consider Problem 9 with the lowest TSR has the most complicated schema, the highest contextual factor. Conversely Problem 7 with the highest TSR among all the problems has a simple schema and the lowest contextual factor.

To understand why exercises are not classified as easily by our system, consider Exercise 2. Normally, by looking at the schema, we would expect that students would do very well on this question, it did not happen because the students received a lot of hints, which decreased the TSR actual greatly. Although we could explain some of the variations using the codes, it looks that schemas are overall not good predictor of the students' success in the exercises since they do not require a lot connection among the pieces. Solving an exercise is pretty much matter of remembering the simple formulas and equations and following a common simple procedure without doing careless mistakes but solving problem requires more knowledge and skills with being able to link the pieces as most important one in addition to the requirements for solving the exercises. Therefore, maybe, the schemas appear to be a better predictor of students' success in solving problems than that in solving exercises.

Table 4.18
The Contextual Factors, Schemas, and the TSRs for Exercises

E	CF	Schemas	TSR (%)
E2	18		50
E13	4		76
E1	3		65
E8	2		78
E7	1		89
E11	1		94
E12	1		94
E6	-2		76
E9	-3		87
E4	-4		71
E10	-5		100
E5	-6		97
E3	-18		85

Conclusion

Finally, we think we got an answer for the question one. The question one was aiming to find the source or sources behind the students' poor performances with the questions, especially with the complex problems. In order to answer this question we checked and investigated:

- Average Number of Pieces
- Number of Piece Types
- Attempt Success Rates
- Schemas along with
    - Contextual Factor
    - Codes Assigned to the Pieces

Based on the overall analysis, we could say that the students' poor performance did not have a significant relationship with the average number of pieces, number of piece types, and the attempt success rates. We therefore could not explain low Total Success Rates with any of those variables. We did find it fruitful to examine the questions' schemas. In this way, we could see how the complexity of how the pieces needed to be linked together increase question difficulty. We discovered that the effect of the complexity of the schemas roughly correlates with the contextual factors.

Because the contextual factor has a good correlation with the schemas, we believe the use of schemas can predict what problems will be difficult for students. In this way, our analysis has predictive power. We already

discussed how this situation is weakened with exercises. To estimate the success of the students in exercises, some diagnostics tests measuring students' declarative knowledge about the facts and events and procedural knowledge might be good enough. The estimation of the students' success in problem solving, on the contrary, is much more complicated and requires consideration of the many variables at the same time.

Our model can predict the students' achievement in stoichiometric problem solving, but it may not work all the time. Since the schemas seem to be promising in explaining the variations in the TSRs, we put the schemas in the center of model. If the problem has a complicated and illinear schema, it usually means the context of the questions are difficult to understand and interpret. Moreover, it means that students might have more trouble in putting their knowledge pieces together because linking the pieces in a way, which fits to the schemas of the problems will be more challenging. The schemas of the problems and the contexts of the questions will determine how the students are going to be successful in linking the knowledge pieces and the success in linking of the knowledge pieces will determine how good performance students will show in solving stoichiometric problems.

Answering the Second Research Question

The second question of our research is:

What are the differences between successful and unsuccessful students in knowledge, ability, and practice?

To answer this question we compared successful to unsuccessful students (as measured by the Chemistry Achievement Test (CAT)) looking at four possible areas of differences:

1. Performance on individual pieces by
    a. Piece type
    b. Problem complexity
    c. Codes received
2. Non-chemistry and chemistry objective errors
    a. Arithmetic errors
    b. Units errors
3. Performance on other cognitive tests (TOLT, DBT, LT, BPCI, and MCAT)

Teachers might categorize their students as successful and unsuccessful based on the different test results but they might not try to find out what makes them successful or unsuccessful. It is tempting to reduce the issue to one or two variables instead of doing an in-depth analysis of the types of knowledge students have and the strategies students use. In

answering the Research Question #2, we attempt to measure and interpret how students are different in terms of their domain-specific knowledge and different strategies they use while solving the questions. Much of what we find confirms the differences cited in the literature, between successful and unsuccessful chemistry students and between experts and novices.

Performance on Individual Pieces By

Piece Types

One might expect that unsuccessful students perform less well than successful students on a few key, "stumbling block," pieces. In fact, we find that unsuccessful students do score significantly lower (at the 95% confidence level) than successful students do, but only on a small number of pieces. The differences are detailed in Table 4.19 and Figure 4.7.

Included in the tables and figures are the results of statistical tests to determine if the differences between successful and unsuccessful students are statistically significant. We ran independent samples t-test and calculated the significances for the differences. We did t-test for the pieces and all other variables, which we examined to understand the differences between the successful and unsuccessful students. The results of the t- tests show that the only observed the significant differences between ASRs of the BEQ, PY, and SR. Two of these pieces are related to the students' domain specific

knowledge and one of them is related to students' cognitive ability, formal (proportional) reasoning ability. This means that unsuccessful students are different from the successful ones in terms of the knowledge and ability.

Table 4.19
The Comparison of the Attempt Success Rates (ASR) of the Successful Subjects to those of Unsuccessful Ones with Each Piece (*Significant difference at the 0.05 level)

SBJ	CAT	WEQ		BEQ.		MP		EF		MF		PY		LR		MC		SR		MR	
		45%		90%		87%		53%		88%		68%		80%		95%		86%		94%	
p values		*.09*		*.03**		*.06*		*.90*		*.13*		*.01**		*.09*		*.12*		*.02**		*.09*	
01	S	73%		100%		88%		33%		100%		67%		0%		98%		67%		100%	
03	S	55%		100%		100%		50%		100%		100%		100%		100%		95%		100%	
07	S	55%		90%		75%		50%		100%		100%		100%		98%		83%		100%	
09	S	36%		100%		100%		67%		100%		75%		100%		97%		94%		100%	
10	S	45%	51%	100%	97%	100%	94%	67%	52%	100%	100%	80%	79%	100%	89%	98%	98%	96%	90%	100%	94%
11	S	45%		100%		100%		100%		100%		75%		100%		100%		95%		100%	
14	S	64%		100%		88%		33%		100%		60%		100%		100%		89%		100%	
15	S	45%		100%		100%		0%		100%		50%		100%		94%		94%		100%	
18	S	36%		82%		100%		67%		100%		100%		100%		98%		95%		50%	
02	U	56%		100%		86%		33%		100%		50%		50%		97%		75%		100%	
04	U	40%		80%		83%		0%		0%		67%		100%		90%		76%		100%	
06	U	36%		80%		75%		50%		100%		60%		0%		91%		71%		100%	
08	U	30%	38%	100%	82%	100%	73%	50%	54%	100%	75%	67%	49%	100%	56%	97%	87%	93%	78%	100%	94%
12	U	64%		100%		100%		100%		100%		50%		100%		100%		89%		100%	
13	U	18%		80%		86%		100%		100%		33%		50%		97%		80%		100%	
16	U	22%		56%		20%		100%		0%		0%		0%		38%		67%		50%	
17	U	40%		60%		33%		0%		100%		67%		50%		83%		75%		100%	

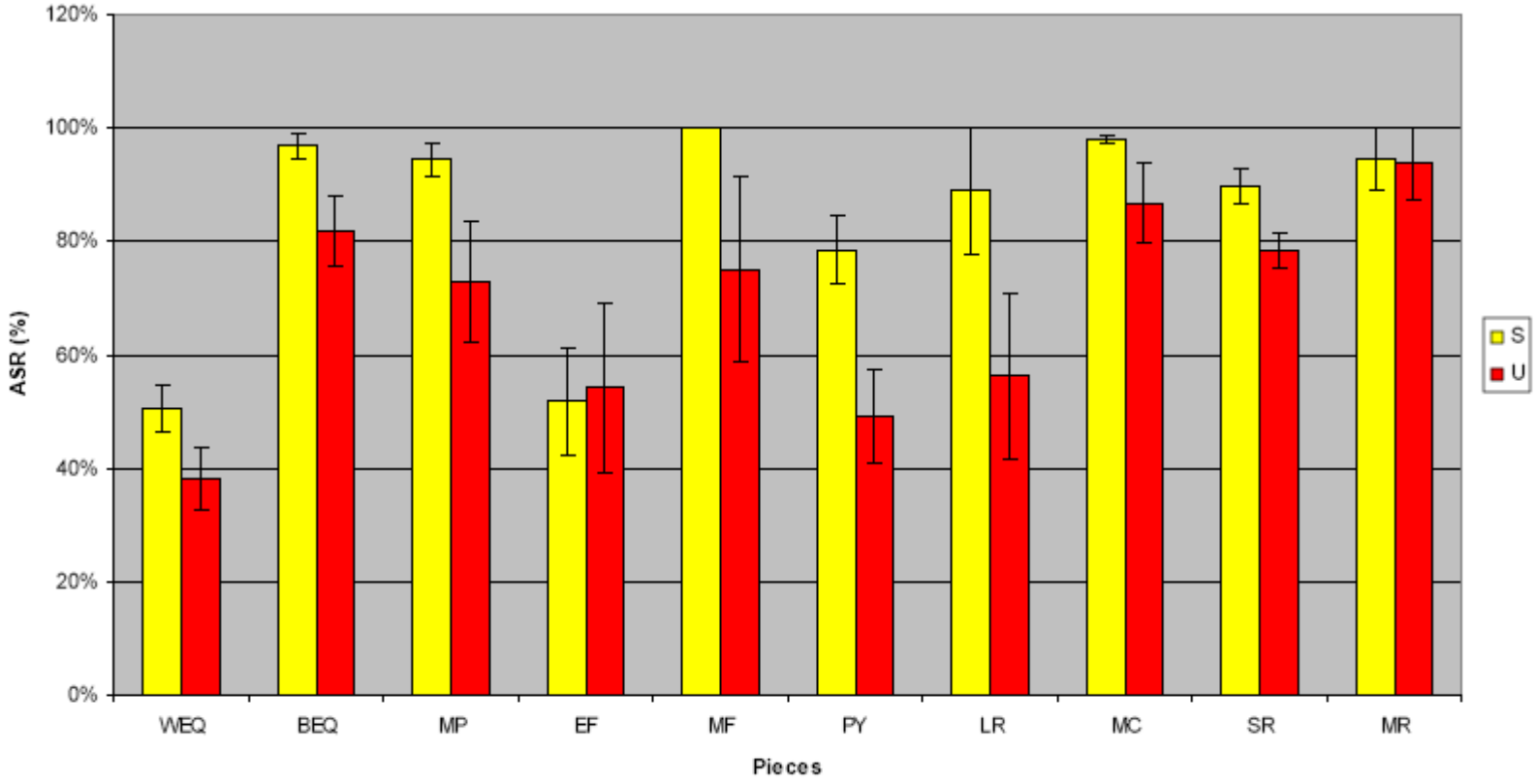


Figure 4.7: The Comparison of the Attempt Success Rates of the Successful Subjects to those of Unsuccessful Ones with Each Piece. Error bars shown are +/- standard error.

After seeing the significant difference for the SR piece, we could not make sense why the students had the same scores with the MR piece. Since the both MR and SR pieces were related to their abilities of doing the ratios, we expected to see the similar results in both of them. This did not happen, however, which shows that the students' abilities using domain specific knowledge depends significantly on the contexts of the questions. For this reason, we thought it would be fruitful to look at the differences between students' success rates in exercises (simple questions) versus problems, (complicated questions). In the Chapter 5, we are going to talk about its implications for teaching.

Problem Complexity

Tables 4.20 and 4.21 and Figures 4.8 and 4.9 clearly show that the differences between successful students and unsuccessful students manifest themselves mainly in complex problems. Moreover, checking the t-test results for the exercises and problems will clearly depict that differences between two groups of the students are much clearer in the complex problems. Out of fifteen exercises, we detect just three statistically significant differences for both groups of the students while among twelve problems we observe significant differences in six of them, especially the ones with the low TSRs. This is a corollary to the conclusion reached in Research Question #1: student success is not determined solely by the pieces involved but is also the

context of the problem. Our conclusion here, however, can be stated even more strongly. The complexities of the problems brought out the differences, which were not clear while students were doing the exercises. In order to find why the differences between two groups of students become clearer as the problem gets more complex, we decided to do further analysis by examining the types and the frequency of the codes assigned to the pieces in successful and unsuccessful students' solutions.

Table 4.20
The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Exercises (*Significant difference at the 0.05 level)

SBJ	CAT	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15
		65%	**50%**	**85%**	**71%**	**97%**	**77%**	**90%**	**79%**	**88%**	**100%**	**94%**	**94%**	**77%**	**94%**	**94%**
p values		*.05**	*.35*	*.17*	*.33*	*.30*	*.90*	*.08*	*.05**	*.13*	*NA*	*.30*	*.30*	*.01**	*.36*	*.30*
01	S	100%	50%	100%	100%	100%	100%	100%	100%	86%	100%	100%	100%	100%	100%	100%
03	S	50%	50%	100%	100%	100%	50%	100%	100%	100%	100%	100%	100%	80%	100%	100%
07	S	100%	50%	50%	50%	100%	100%	100%	100%	100%	100%	100%	100%	80%	100%	100%
09	S	100%	50%	50%	50%	100%	100%	100%	50%	100%	100%	100%	100%	80%	100%	100%
10	S	100%	50%	50%	50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
11	S	50%	50%	100%	100%	100%	100%	100%	100%	86%	100%	100%	100%	80%	100%	100%
14	S	50%	100%	100%	100%	100%	50%	100%	100%	100%	100%	100%	100%	80%	100%	100%
15	S	50%	50%	100%	100%	100%	0%	100%	100%	86%	100%	100%	100%	80%	100%	100%
18	S	100%	50%	50%	50%	100%	100%	100%	88%	86%	100%	100%	100%	80%	0%	100%
AVERAGE		**78%**	**56%**	**78%**	**78%**	**100%**	**78%**	**100%**	**93%**	**94%**	**100%**	**100%**	**100%**	**84%**	**89%**	**100%**
02	U	50%	100%	100%	100%	100%	100%	67%	100%	86%	100%	100%	100%	80%	100%	100%
04	U	50%	50%	100%	50%	100%	50%	50%	100%	100%	100%	100%	100%	40%	100%	100%
06	U	50%	50%	100%	50%	100%	50%	100%	88%	71%	100%	100%	100%	60%	100%	100%
08	U	50%	50%	100%	100%	100%	50%	100%	13%	100%	100%	100%	100%	80%	100%	100%
12	U	100%	50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	80%	100%	100%
13	U	50%	50%	50%	50%	100%	100%	100%	50%	86%	100%	100%	100%	60%	100%	100%
16	U	0%	0%	100%	0%	50%	100%	0%	0%	29%	100%	0%	100%	60%	100%	0%
17	U	50%	0%	100%	50%	100%	50%	100%	38%	71%	100%	100%	0%	80%	100%	100%
AVERAGE		**50%**	**44%**	**94%**	**63%**	**94%**	**75%**	**77%**	**61%**	**80%**	**100%**	**88%**	**88%**	**68%**	**100%**	**88%**

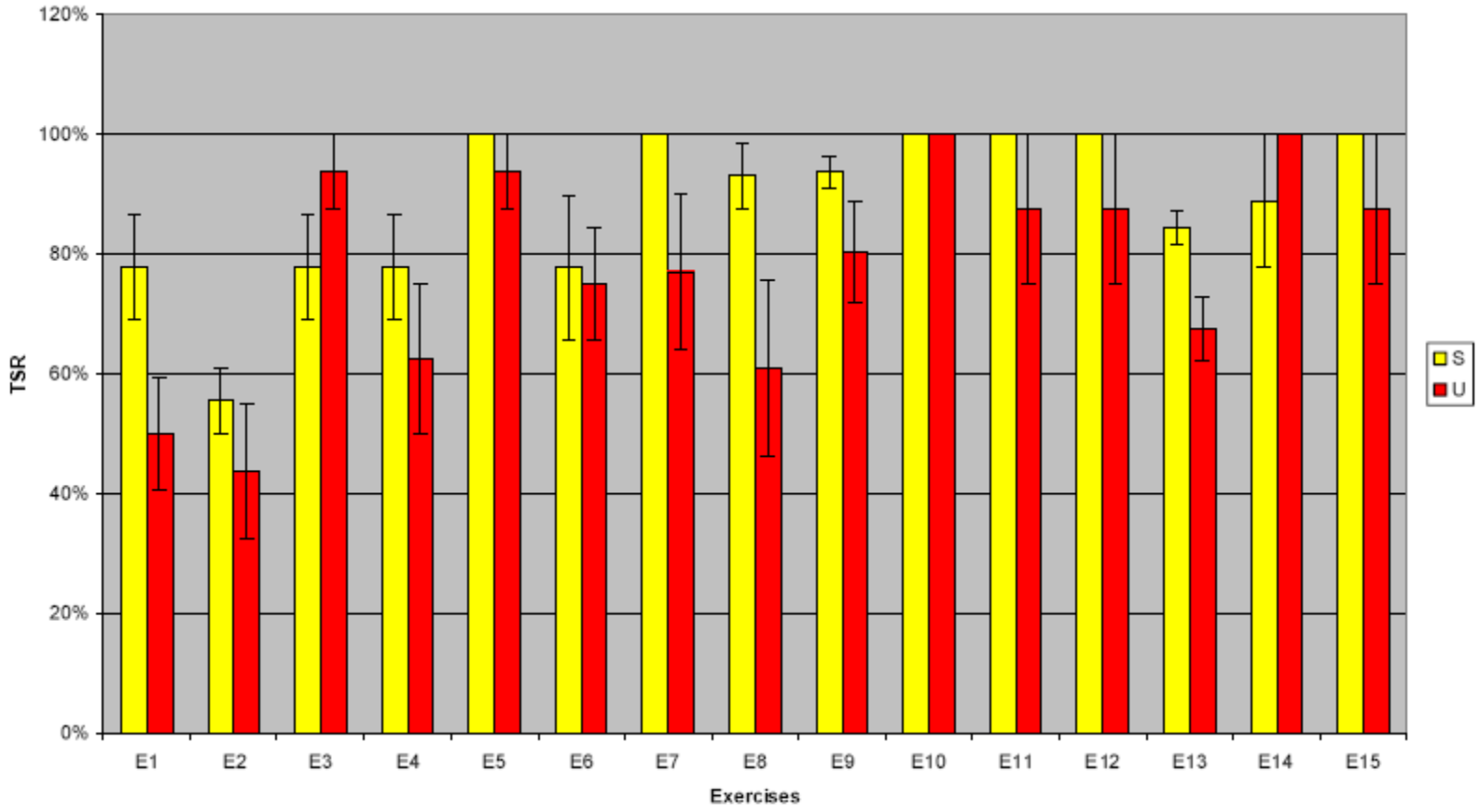


Figure 4.8: The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Exercises

Table 4.21
The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Problems (*Significant difference at the 0.05 level)

SBJ	CAT	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
		83%	61%	51%	74%	64%	65%	94%	55%	44%	86%	72%	72%
p values		*.08*	*.04**	*.05**	*.00**	*.15*	*.00**	*.20*	*.00**	*.16*	*.30*	*.52*	*.05**
01	S	100%	42%	33%	100%	80%	75%	100%	100%	38%	40%	83%	100%
03	S	100%	100%	100%	100%	80%	100%	100%	33%	63%	100%	67%	100%
07	S	100%	83%	50%	100%	60%	38%	100%	67%	50%	100%	83%	100%
09	S	100%	42%	67%	71%	83%	100%	100%	67%	63%	100%	83%	100%
10	S	50%	75%	67%	100%	83%	100%	100%	100%	63%	100%	100%	100%
11	S	100%	100%	100%	100%	80%	100%	100%	100%	33%	100%	100%	43%
14	S	100%	42%	100%	100%	80%	60%	100%	100%	57%	100%	83%	86%
15	S	100%	75%	0%	100%	20%	100%	100%	67%	63%	100%	50%	43%
18	S	100%	100%	83%	100%	80%	100%	100%	100%	14%	100%	33%	100%
AVERAGE		94%	73%	67%	97%	72%	86%	100%	81%	49%	93%	76%	86%
02	U	100%	58%	33%	43%	80%	75%	100%	0%	29%	100%	83%	43%
04	U	50%	42%	33%	43%	80%	63%	100%	33%	14%	100%	67%	100%
06	U	100%	25%	33%	71%	60%	17%	100%	67%	25%	40%	100%	86%
08	U	100%	75%	50%	71%	50%	20%	100%	0%	57%	100%	33%	43%
12	U	100%	80%	100%	86%	83%	100%	80%	0%	57%	100%	100%	43%
13	U	50%	33%	0%	29%	0%	40%	100%	0%	50%	100%	100%	43%
16	U	0%	0%	0%	14%	20%	0%	20%	0%	33%	0%	17%	0%
17	U	50%	45%	0%	0%	50%	0%	100%	67%	33%	80%	33%	86%
AVERAGE		69%	45%	31%	45%	53%	39%	88%	21%	37%	78%	67%	55%

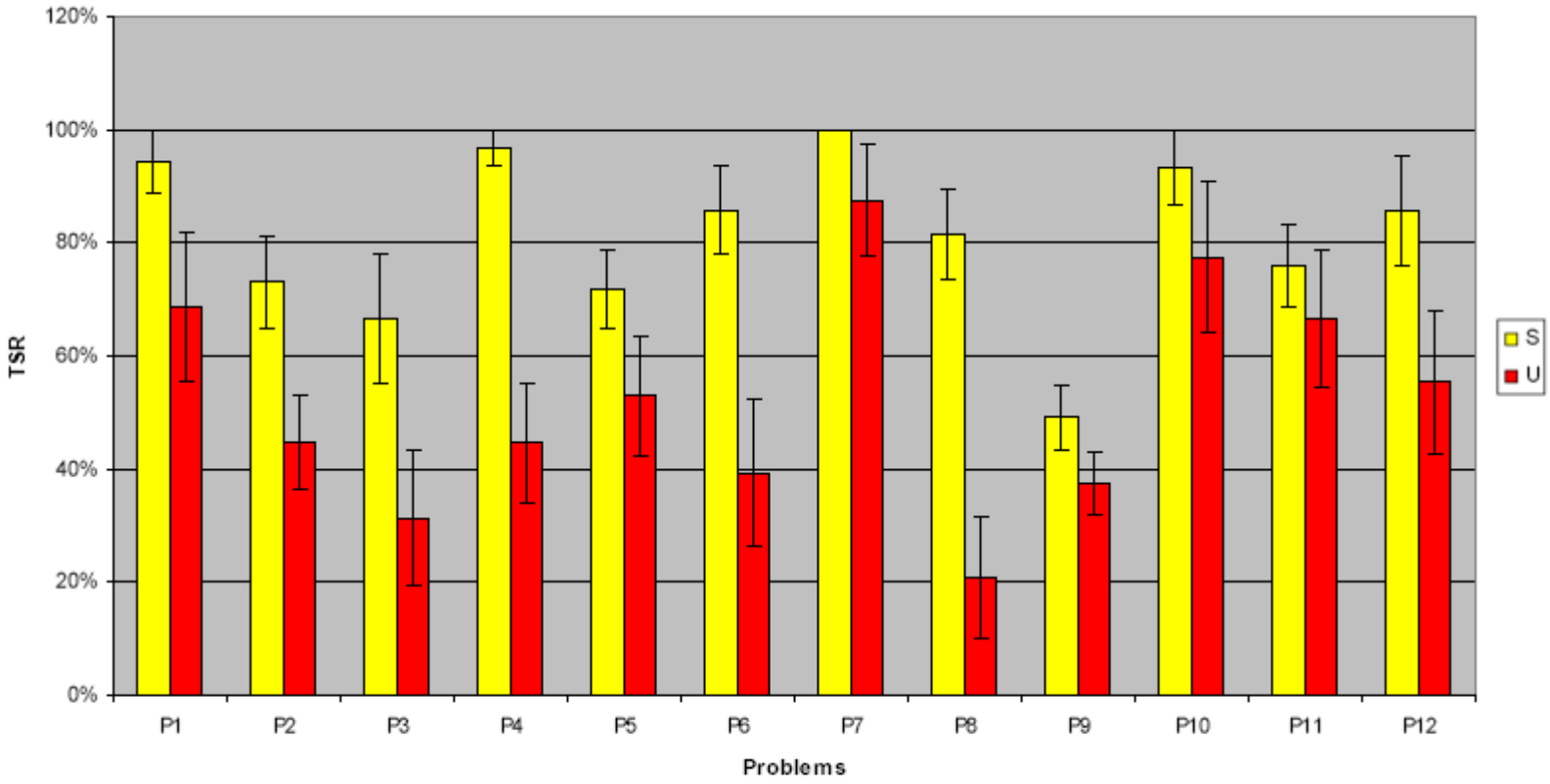


Figure 4.9: The Comparison of the Total Success Rates of the Successful Subjects to those of Unsuccessful Ones with Problems

Codes Received

We again prepared different tables and figures for the exercises and problems to illuminate the differences in those types of the questions. In the tables, the first thing we noticed was that the total number of the pieces was not the same for successful and unsuccessful students since we had nine successful students and eight unsuccessful students. As we explained before, one of the unsuccessful students after first think-aloud protocol quit from the study because of time constraint. Since the total numbers were different for each group of the students, we could not use the number of pieces to do further analysis to explore the characteristics of the successful and unsuccessful students. Therefore, we calculated and used the percentage of the codes assigned to the pieces done by successful and unsuccessful students.

Like in the examination of the TSRs of the problems and exercises, we found that differences among the codes assigned to the pieces done by successful and unsuccessful students get much more obvious and significant in the complex problems than they are in the exercises. We found out that, statistically speaking, successful students are different from the unsuccessful ones in four categories: DD, DSE, UDI, and S in the problems but just in one category, S, in the exercises. It is surprising to see that successful students are different from unsuccessful ones in just one category in the exercises but

it is supporting our findings in the previous section and in the Research Question #1.

Table 4.22
The Comparison of the Codes Assigned to the Pieces Done by the Unsuccessful and Successful Students in the Exercises (*Significant difference at the 0.05 level)

SBJ	CAT	NR		CD		UDI		DD		DSE		URH		UG		S		T	
		4		1		51		23		3		41		1		539		663	
p values		*.90*		*.30*		*.28*		*.06*		*.30*		*.55*		*.30*		*.04**			
01	S	0	2	0	0	1	12	0	5	0	0	1	23	0	0	37	309	39	351
03	S	0		0		2		0		0		2		0		35		39	
07	S	0		0		1		0		0		3		0		35		39	
09	S	0		0		0		3		0		4		0		32		39	
10	S	1	0.6%	0	0.0%	0	3.4%	0	1.4%	0	0.0%	3	6.6%	0	0.0%	35	88.0%	39	
11	S	1		0		1		0		0		3		0		34		39	
14	S	0		0		2		0		0		1		0		36		39	
15	S	0		0		2		2		0		2		0		33		39	
18	S	0		0		3		0		0		4		0		32		39	
02	U	0	2	0	1	3	39	0	18	0	3	1	18	0	1	35	230	39	312
04	U	1		1		3		2		0		2		0		30		39	
06	U	0		0		6		1		0		2		0		30		39	
08	U	0		0		2		5		0		2		0		30		39	
12	U	0	0.6%	0	0.3%	0	12.5%	0	5.8%	0	1.0%	2	5.8%	0	0.3%	37	73.7%	39	
13	U	0		0		3		3		0		4		0		29		39	
16	U	0		0		13		6		3		3		1		13		39	
17	U	1		0		9		1		0		2		0		26		39	

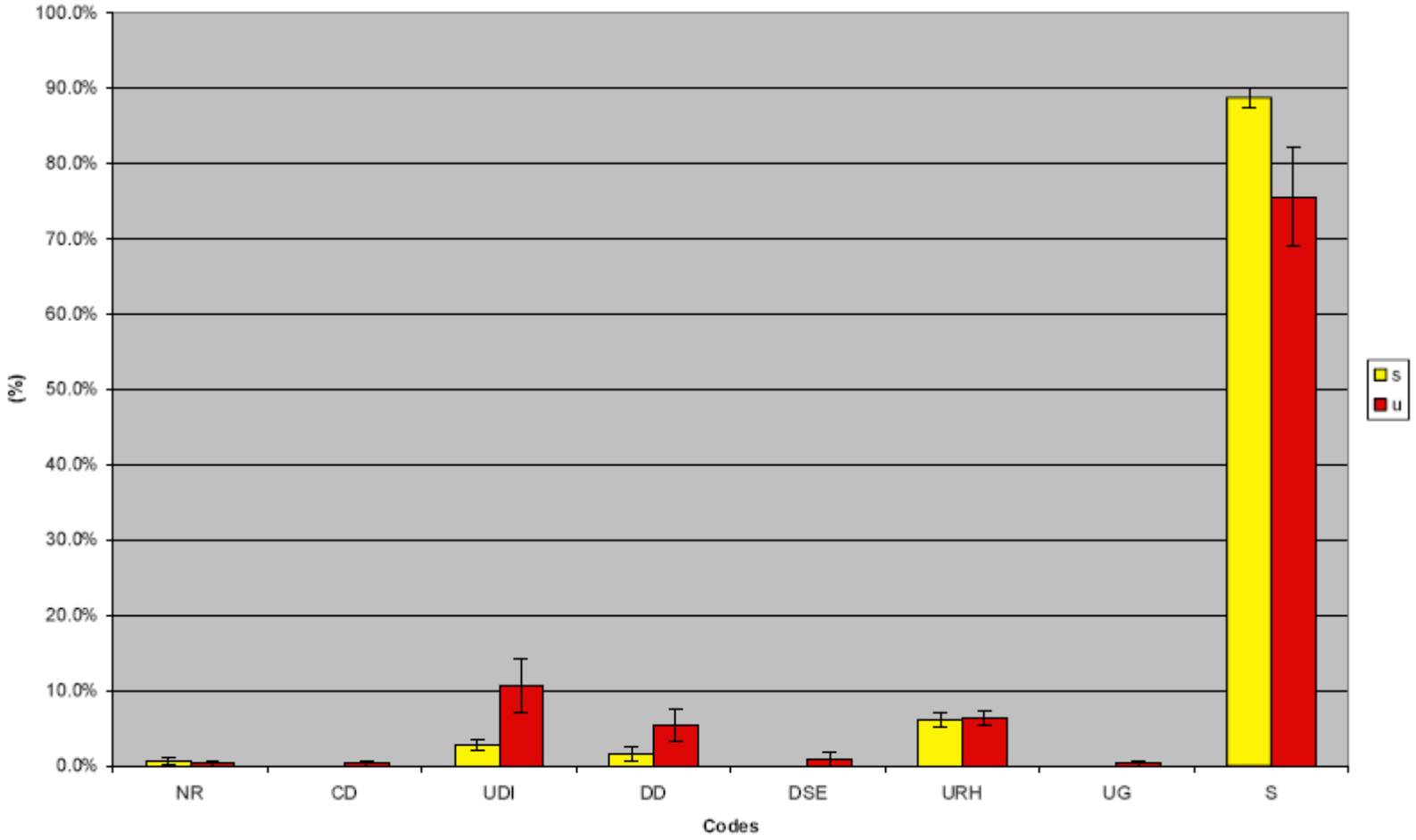


Figure 4.10: Percents of the Codes Assigned to the Pieces Done By Successful and Unsuccessful Students in the Exercises

Table 4.23
The Comparison of the Codes Assigned to the Pieces Done by the Unsuccessful and Successful Students in the Problems (*Significant difference at the 0.05 level)

SBJ	CAT	NR		CD		UDI		DD		DSE		URH		UG		S		T	
		146		14		108		221		24		38		6		786		1343	
p values		*.90*		*.73*		*.00**		*.00**		*.05**		*.90*		*.07*		*.00**			
01	S	6	75	0	8	10	38	10	62	1	7	2	20	0	0	50	501	79	711
03	S	13		0		1		4		1		2		0		58		79	
07	S	7		1		6		8		0		2		0		55		79	
09	S	11		1		4		8		2		2		0		51		79	
10	S	4	10.5%	1	1.1%	3	5.3%	3	8.7%	0	1.0%	3	2.8%	0	0.0%	65	70.5%	79	
11	S	7		1		1		5		0		2		0		63		79	
14	S	9		1		6		5		1		2		0		55		79	
15	S	12		1		6		13		2		2		0		43		79	
18	S	6		2		1		6		0		3		0		61		79	
02	U	6	71	1	6	8	70	16	159	1	17	2	18	1	6	44	285	79	632
04	U	7		3		9		15		1		2		0		42		79	
06	U	7		0		12		17		1		3		0		39		79	
08	U	8		0		5		18		3		3		0		42		79	
12	U	14	11.2%	0	0.9%	4	11.1%	8	25.2%	1	2.7%	2	2.8%	0	0.9%	50	45.1%	79	
13	U	10		1		9		24		2		2		0		31		79	
16	U	11		0		12		39		6		2		3		6		79	
17	U	8		1		11		22		2		2		2		31		79	

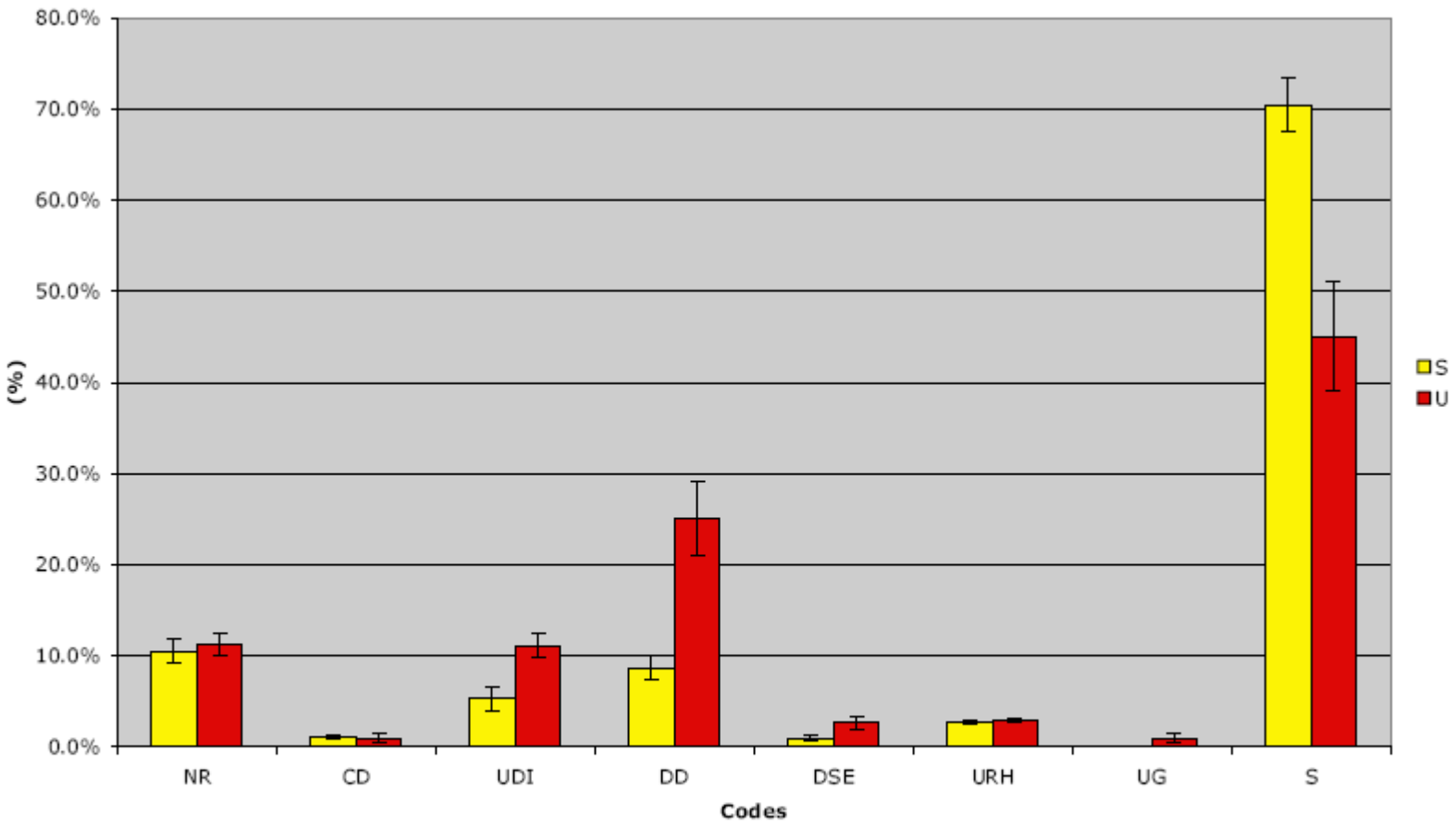


Figure 4.11: Percents of the Codes Assigned to the Pieces Done By Successful and Unsuccessful Students in the Problems

The code S was the only code showed a significant difference in the exercises. Moreover, it was the only common code in which we observed significant difference between the successful and unsuccessful students in both exercises and the problems. We therefore checked and compared the percent of the code S in both tables for both groups. The percents of the code S for successful and unsuccessful students were 88.0 % and 73.7% in the exercises and 70.5% and 45.1% in the problems, respectively, which meant that successful students did more pieces correctly than unsuccessful students in both exercises and problems. This finding, however, was not interesting for us because we were expecting to see that the percent of the code S was greater than that of unsuccessful students. What is more interesting is to consider the ways in which the unsuccessful students were not given an S.

In the rest of code analysis, we did not focus on the codes collected from the exercises any more since we could not observe any significance difference other than the difference in the code S. Rather, we investigated the codes coming from the problems. When an unsuccessful student was not successful, roughly one-fifth of the time (11.1% UDI out of 54.9% total non-S codes) it was because they explicitly did a problem incorrectly (UDI). Clearly, unsuccessful students are more likely on a given piece to make an explicit mistake than successful students are. On the other hand, when seen as a fraction of their mistakes, the difference is less striking. In fact, when a

successful student was not successful, roughly one-sixth of the time (5.3% out of 29.5%) it was because they explicitly did the problem incorrectly. And so, while it is true that unsuccessful students simply have more difficulties that successful ones, the fraction of their difficulties due to explicit mistakes is actually quite similar.

A more striking distinction between successful and unsuccessful students is the frequency with which unsuccessful students do not know what to do (DD) or do something unproductive (DSE). When combining these two similar codes, we see that they contribute to nearly half of non-successful pieces for unsuccessful students (27.9% out of 54.9% total). On the other hand, these codes contribute to only just over a quarter (9.7% out of 29.5% total) of the non-successful codes for successful students. This piece of the data was illuminating a very important difference between the successful and unsuccessful students' characteristics and partially accounting for why the unsuccessful students showed poorer performance almost in all the pieces and the questions. The fundamental problem and difficulty on the unsuccessful students' part appeared to be that unsuccessful students could not understand the question well enough, see what the questions were really asking, and were unable to choose an efficient method which could take them from where they were to where they wanted to be. The difference between the percents of the UG code also supported this finding although its difference did not appear to be significant. The students when they did not know what

method needed to be followed and what pieces needed to be done, they did nonsense calculations or made guesses based on irrelevant data and received the either the code DSE or the code UG. It occurred to us that unsuccessful students certainly needed more exercise and familiarity with the types of the problems and knowledge about the pieces.

On the other hand, the results showed that there was not any significant difference between the percents of the codes NR, CD, and URH assigned to the pieces done by the successful and the unsuccessful students. Seeing that the percent of the code URH of unsuccessful students was very close to that of the successful students was good for us because it showed that we provided almost the same number of the hint for the students in each group. Although providing hints was all right, we tried to give the minimum number of the hints because we were aware that each hint could influence the reliability and objectivity of the study. I think it was tolerable to have the little difference between the groups' percents of the code URH since we presented the hints only to those students who did not have any idea what to do at the beginning of the question and could not show their knowledge about the pieces involved in the question. More importantly, none of those hints was directly about our pieces except the ones, which were about the writing chemical equations and needed at the beginning. They were provided to help the students initiate the solutions.

Non-Chemistry and Chemistry Objective Errors

Arithmetic Errors

Beyond pieces that were specific to chemistry, we also wanted to see if the students were careful and motivated to do the problems correctly or they did simple errors and mistakes in their solutions. One type of error that is common in student work in a chemistry class is simple arithmetic errors. Although while we were analyzing the success with the pieces and the problems, we ignored the simple math and calculation errors, in this section we address them because in real tests and classrooms, accuracy with these processes are valued and assessed.

Other types of the errors, which we examined and identified as simple mistakes, were transferring numbers erroneously from the questions to solutions or from the calculators to the solutions and entering numbers into calculators incorrectly. The difference between successful and unsuccessful students' arithmetic errors appeared to be statistically significant.

After the analysis of the errors, we were happy to see that the number of the errors for each group was low. Almost all the mistakes were very simple ones. Considering the simplicity and frequency of the mistakes, we think that students made those mistakes mostly because of being careless or anxious. Especially, considering the complexity of the problems, the nature of

some students, who were very shy, and feeling of being videotaped and watched all the time while solving the problems, we started to believe that anxiety played an important role in students' errors although we did not do a detailed analysis for the sources of the errors.

Table 4.24
The Comparison of the Errors with Algorithm and the Calculators
(*Significant difference at the 0.05 level)

SBJ	CAT	Errors Related to Algorithm		Incorrect Transfer of the Numbers from the Question & Error with Using the Calculator	
p values		*.02**		*0.14*	
1	S	1	8	1	8
3	S	0		1	
7	S	1		0	
9	S	0		0	
10	S	0		1	
11	S	2		0	
14	S	2		3	
15	S	2		1	
18	S	0		1	
2	U	2	25	0	16
4	U	1		1	
6	U	7		5	
8	U	0		1	
12	U	1		1	
13	U	5		5	
16	U	5		1	
17	U	4		2	

The analysis of the errors one more time showed that the problem solving process was indeed extremely complicated. Students did not only need to have a competitive amount of domain-specific knowledge, several skills and

abilities such as proportional reasoning, and a good set of strategies to use when needed but they also needed to be accurate and flawless in order to reach the right answers and be successful in their problem solving attempts.

Units Error

While checking the errors we also noticed that students were doing some chemistry related errors, which were about the units. The analysis of the units revealed that successful students again were significantly different from the unsuccessful students as depicted in the Table 4.25.

Table 4.25
The Comparison of the Unit Errors (*Significant difference at the 0.05 level)

SBJ	CAT	Using Units					
		Used Correctly		Used Incorrectly		Did not Use	
p values		*.00**		*.00**		*0.13*	
1	S	18	162.0 (100%)	0	0	0	0
3	S	18		0		0	
7	S	18		0		0	
9	S	18		0		0	
10	S	18		0		0	
11	S	18		0		0	
14	S	18		0		0	
15	S	18		0		0	
18	S	18		0		0	
2	U	17	127.0 (88%)	1	15.0 (11%)	0	2.0 (1%)
4	U	17		0		1	
6	U	17		1		0	
8	U	17		1		0	
12	U	17		1		0	
13	U	15		3		0	
16	U	12		5		1	
17	U	15		3		0	

Successful students in all questions reported their answers along with the associated units. Moreover, they always used the units correctly. The unsuccessful students, however, were not that successful with using the units. Although the percentage of unsuccessful students' correct use of the units was considerably high, some students still used the units incorrectly and some students occasionally did not use the units at all and reported their answers without the units. The incorrect use of the errors might be result of the poor understanding of the concepts or careless solutions.

The final piece of data on the Table 4.25 we checked if the number of the cases where students did not use the units at all was high or low. The table showed that it is significantly low, which meant that students were aware of the importance of the units and they gained that habit of using the units. Here, we should also make something clear about the examination of the units. While investigating the students' habits of using units and errors related to the units, we did not check all the numbers and units in the solutions because checking all the numbers would be a very challenging task and we did not have that much time and interest. Rather, we just examined the units of the final answers to get an idea about students' understanding of the concepts and habits of using the units.

Performance on Cognitive Tests

In the study, we exploited the qualitative data as well as the quantitative data to explain the differences between the successful and unsuccessful students' performances in the stoichiometry problems. The qualitative data was obtained through the audio recordings and observations we did during the think-aloud protocols. On the other hand, the quantitative data was gathered using the students' solutions, which students provided during the think-aloud protocols and the results of the several tests such as the mole concept achievement test, the test of logical thinking, the digits backward test, the Longeot test, and the Berlin particle concept inventory test. Each test, as we discussed previously in detail in methodology section, was employed to find out different cognitive abilities of students. For example, the TOLT was for the measurement of the students' ability of reasoning logically and the DBT for the measurement of the students' working memory capacities.

The results of all the tests in Figure 4.15 below depicts that successful and unsuccessful students' knowledge about the subject matter and abilities were different from each other. Although the figure shows that the results of all the tests were different for each group of the students, the Table 4.29 reveals that the differences for most of the tests were not significant. The statistically significant differences were observed in TSRs, TOLT and MCAT.

The TSR is the most important piece of quantitative data and our dependent variable. These results clearly depicted that successful students' performances with the stoichiometry problems used in the study were much better than that of unsuccessful students.

In the same manner, successful students appear to have a better understanding of the mole concept and proportional reasoning ability. We know that solving the stoichiometry problems mostly requires students do MC and SR pieces as can be seen on Tables 4.9 and 4.10. This means that success in solving the stoichiometry problems mostly depends on the success on the mole concept and stoichiometric ratio, which requires a good proportional reasoning ability.

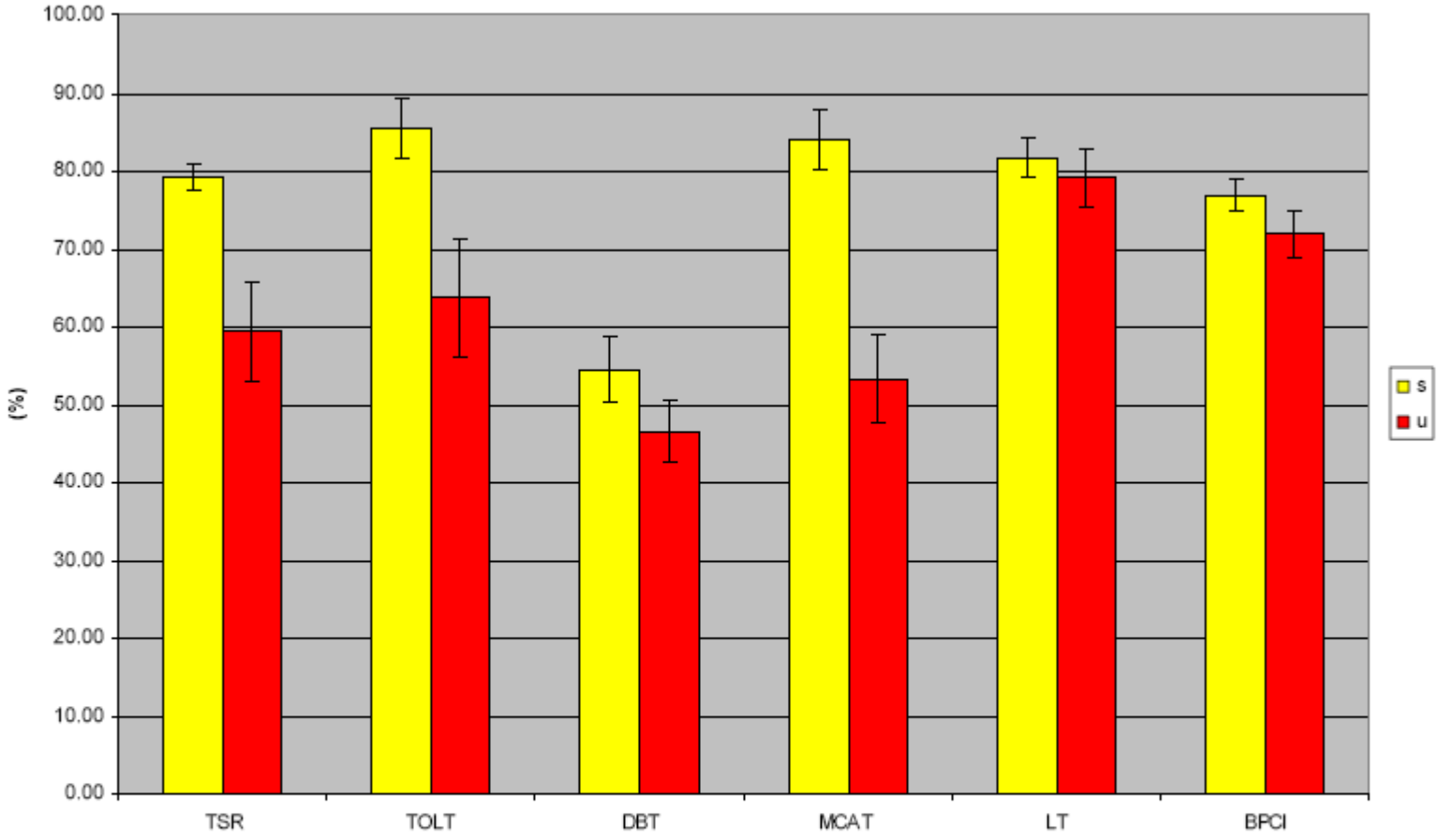


Figure 4.12: Comparison of the Test Results for Cognitive Variables Affecting the Problem Solving Performance

Table 4.26
Results of the Tests for Cognitive Variables Affecting the Problem Solving Success (*Significant difference at the 0.05 level)

SBJ	CAT	TSR	TOLT	DBT	MCAT	LT	BPCI
p values		***.00****	***.02****	***.20***	***.00****	***.60***	***.20***
01	S	79.1	100	5 (45)[a]	77.8	85.7	80.0
03	S	81.6	90	6 (55)	80.0	95.2	78.6
07	S	79.7	70	7 (64)	62.2	76.2	68.6
09	S	73.3	80	8 (73)	91.1	81.0	77.1
10	S	86.0	100	8 (73)	91.1	83.3	72.9
11	S	83.5	90	6 (54)	93.3	81.0	80.0
14	S	81.0	70	4 (36)	91.1	69.0	90.0
15	S	69.5	90	5 (45)	73.3	88.1	74.3
18	S	79.6	80	5 (45)	97.8	76.2	71.4
A		**79.2**	**85.6**	**6.0**	**54.5**	**81.7**	**77.0**
02	U	72.7	100	6	75.6	66.7	81.4
04	U	65.0	70	5 (45)	60.0	61.9	74.3
06	U	63.1	50	6 (54)	75.6	81.0	77.1
08	U	65.0	40	5 (45)	42.2	83.3	78.6
12	U	79.1	60	4 (36)	51.1	85.7	71.4
13	U	56.8	90	5 (45)	51.1	95.2	64.3
16	U	20.5	50	7 (64)	31.1	78.6	55.7
17	U	53.0	50	3 (27)	40.0	81.0	72.9
A		**59.4**	**63.8**	**5.1**	**46.6**	**79.2**	**72.0**

[a] The values in the parentheses are the percents calculated by dividing the DBT scores by 11, which is the highest number of digit in the DBT test.

We therefore think that significant differences between the successful and unsuccessful students' MCAT and TOLT score are important in terms of explaining the unsuccessful students' poor performances and low TSRs compared to those of successful ones in solving stoichiometry problems.

In the next section where we answer the third research question, we talk about other aspects of these tests and present statistical results including the nonparametric correlation coefficients.

More Differences: Problem Solving Habits

In addition to the differences between successful and unsuccessful students' performances on pieces, types of errors they made, and cognitive abilities, we also determined the differences in their problem solving habits, which can be summarized under a few titles:

a. Perspective when starting problems (conceptual vs. algorithmic)

b. Fluency of work (fluent vs. hesitant)

c. Perspective of overall approach (conceptual vs. algorithmic) and methods (working forward vs. means-end)

d. Checking final answer (checking vs. not checking)

These differences presented in Appendix I were not discussed here in detail since they need more work and analysis to be functionalized and operationalized.

Answering the Third Research Question

The third research question investigates several broad cognitive abilities to determine whether or not they correlate with ability to succeed in solving stoichiometry problems. This research question is:

What are the roles of cognitive development, proportional reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in successful and unsuccessful students' problem solving success in stoichiometry?

To answer this question we employed mainly the quantitative, statistical methods. Each broader cognitive ability was measured with validated examinations taken from the literature. These are:

- Longeot Test (LT) for cognitive development,
- Test of Logical Thinking (TOLT) for proportional reasoning ability,
- Digit Backwards Test (DBT) for working memory capacity,
- Berlin Particle Concept Inventory (BPCI) for conceptual understanding of the particle nature of matter,
- Mole Concept Achievement Test (MCAT) for the mole concept.

Each test resulted in a quantitative score for each subject, for each cognitive ability. We did statistical analysis using the scores from the think-aloud protocols and the other cognitive abilities. We used the nonparametric

statistical methods because the number of the students participated in the study was not large enough to produce a smooth normal distribution.

Table 4.27
Descriptive Statistics for the Cognitive Ability Tests

	N	Range	Minimum	Maximum	Mean	SD
TSR	17	65.5	20.5	86.0	69.9	17.0
CAT	17	73.3	20.0	93.3	56.9	23.1
LT	17	33.3	61.9	95.2	80.5	8.9
TOLT	17	60.0	40.0	100.0	75.3	19.7
DBT	17	5.0	3.0	8.0	5.6	1.4
BPCI	17	34.3	55.7	90.0	74.6	7.5
MCAT	17	66.7	31.1	97.8	69.7	20.8

Descriptive statistics for all cognitive tests are given in Table 4.30, along with results of the Chemistry Achievement Test (CAT), which was used to sort students to the successful and unsuccessful groups, and the Think Aloud Protocol scores (TSR). All scores are given out of a maximum possible of 100% except for the DBT scores, which, in theory, have no maximum.

Although our main concern for Research Question #3 is whether the cognitive abilities correlate with the TSR, two of the cognitive abilities can be considered independently because there are norms to compare against. We will consider the Longeot and the DBT.

Descriptive Statistics for the Longeot Test and Digit Backward Test

The Longeot test was used to measure the students' cognitive developments and the results showed that our all students were at formal operational stage. This meant that our students were capable of dealing with abstract concepts. This is consistent with Ward et al's (1981) findings. We are going to discuss this consistency in detail in the Chapter 5.

The results of the DBT indicates that our students' working memory capacity, on average, is lower than the general population. In the DBT, I used different numbers with the varying numbers of digits. The number of digits used in the test ranged from 2 to 11. Miller (1956) found that the amount of information you can remember or process is measured in units called "chunks". According to his theory, we can remember about 7±2 such chunks in short-term memory, which sometimes referred to as primary or working memory. Thus, the highest number of chunks people can be expected to remember is 9 and the lowest number of chunks is 5. In our study, we defined the chunks as the digits of the numbers (Opdenacker et al., 1990) and set up the highest number of digits as 11 in case someone among our students could have exceptionally good working memory capacity. However, nobody in our sample of students reached the highest number of digit, 11. The highest number of digit remembered was 8 and the lowest one was 3. Our students

had a mean of 5.6. This is 1.4 digits less than would be expected for an average person.

Descriptive Statistics for the Mole Concept Achievement Test and Berlin Particle Concept Inventory

In comparing standard deviations we get some indication of the diversity of abilities amongst our students for the various tests. The greatest range and standard deviation was associated with the results of the MCAT, which meant that our group of students had the most diversity in terms of the understanding of the mole concept. On the other hand, the BPCI test results and the Longeot tests had of the lowest ranges and the standard deviations. This might mean that our students had basically the same level of understanding of particulate nature of matter and cognitive development. We are however aware that these assertions might be incorrect. It could also be possible that the tests just do not have many questions that have good discriminating ability. For example, it could be that these tests have some questions that everybody is able to do because they are so simple and other questions, which are impossible for anybody to do. If these were the cases, we would get a small standard deviation not because the students all have the same abilities but because none of the test items discriminates very well.

Table 4.28

The Nonparametric Correlations among the Several Cognitive Variables Affecting the Subjects' Problem Solving Performances (FOR ALL SUBJECTS)

			TSR	MCAT	TOLT	BPCI	DBT	LT	CAT
Spearman's rho		N	17	17	17	17	17	17	17
	TSR	Correlation Coefficient	1.000	.870(**)	.508(*)	.314	.234	-.025	.948(**)
		Sig. (2-tailed)	.	.000	.037	.220	.367	.925	.000
	MCAT	Correlation Coefficient		1.000	.568(*)	.468	.283	-.115	.914(**)
		Sig. (2-tailed)		.	.017	.058	.272	.661	.000
	TOLT	Correlation Coefficient			1.000	.286	.277	.231	.491(*)
		Sig. (2-tailed)				.265	.282	.372	.045
	BPCI	Correlation Coefficient				1.000	-.088	-.117	.412
		Sig. (2-tailed)					.737	.656	.101
	DBT	Correlation Coefficient					1.000	-.086	.169
		Sig. (2-tailed)						.743	.517
	LT	Correlation Coefficient						1.000	-.037
		Sig. (2-tailed)						.	.887
	CAT	Correlation Coefficient							1.000
		Sig. (2-tailed)							.

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Correlations between the Total Success Rates and Cognitive Variables

The most important data for addressing Research Question #3 is the correlations (or lack thereof) between the TSR and the measured cognitive abilities. Because our sample size was too small to produce smooth, normal data, we used the nonparametric statistical tests to calculate Spearman's correlation coefficients. Each measured cognitive ability was treated as an independent variable in our study and TSR results were treated as the dependent variable.

Correlation with the CAT

The highest correlation coefficient found was between the CAT and the TSR results. It was an important sign for us to believe that the CAT was a good instrument to choose the subjects. This shows that it was an effective tool to classify the students as successful and unsuccessful since the CAT showed the most significant correlation with the TSR results. Beyond this assurance, the correlation is an uninteresting one. The questions on the CAT were also stoichiometry problems and so a high correlation with the stoichiometry problems used for the TSR should be expected.

Correlation with the TOLT

Although the correlation coefficient ($r= .508$, $p<.05$) for the TOLT was not very great, it was still had the statistical significance. Having ability to reason logically and proportionally is an important student characteristic influencing the students' problem solving in stoichiometry. Students have to reason logically or need to have logical thinking ability in order to show high performances in solving the stoichiometry problems. This is not surprising because we know that students need to do many SR pieces while solving the stoichiometric problems. It is therefore important to have a good proportional reasoning because it is one of requirements to be able to do SR pieces and get a correct answer in the stoichiometry problems. In the Chapter 5, we are going to discuss our findings in detail and compare them to others' findings.

Correlation with the MCAT

The correlation coefficient ($r= .870$, $p<.01$) for the MCAT was large. Having a good conceptual understanding of the mole concept influences the students' problem solving performances in stoichiometry. Students have to have good knowledge of the mole concept in order to show high performances in solving the stoichiometry problems. This is not surprising because from the analysis of the pieces we know that MC is the most frequently used piece in solving the stoichiometry problems. Its mastery is essential do be successful in solving the stoichiometry problems. We will discuss how this finding is

consistent with previous research in Chapter 5 and explain why we believe that the high correlation between the TSR and MCAT is not surprising.

We also see that on the Table 4.31, in addition to the significant correlations between the TSR and the TOLT and between the TSR and the MCAT, the TOLT is significantly correlated with the MCAT, which meant if someone had a good understanding of the mole concept, he had most likely a good logical thinking ability as well.

Correlation with the LT, DBT, and BPCI

Other variables, LT, DBT, and BPCI, might have possibly affected the students' performance but the statistical test did not reveal any other relation. Thus, we assumed that three other tests, variables, did not significantly influence the students' performance in solving the problems. Again, in the Chapter 5, we will talk about these three tests separately and share the other researchers' findings related to these three variables.

Correlation between the Cognitive Variables and the Pieces

The last test and analysis was between the cognitive variables and the pieces used in solving the stoichiometric problem solving. We did this test because we observed a high correlation between some of the cognitive variables, TOLT and MCAT, and the TSR. The TSR is the combination, in

other words, average success rates of the students with several pieces. Thus, the nature of the correlation between the TOLT and the MCAT and the TSR averages over some of the details available if we look at the individual pieces. We did not know in advance what piece or pieces inside the TSR were really correlated with the TOLT and the MCAT. We can answer this by doing a correlation test among the cognitive variables and the pieces.

The results were very surprising for us because in addition to the correlation between the TOLT and the MCAT and the some pieces, we observed a significant correlation between the BPCI and the WEQ and BEQ pieces. Although we did not observe a significant correlation between the BPCI and the TSR, we here observed a significant correlation between the BPCI and two pieces. It looks that writing equations and balancing equations were influenced by the students' knowledge of particle model.

The TOLT was surprisingly did not correlate with the SR although it showed a significant correlation with the TSR. On the other hand, the MCAT showed significant correlation with half of the pieces. As we expected, it showed the highest correlation with the MC piece. Other pieces the MCAT showed significant correlation were SR, BEQ, MP, and PY.

Again, the cognitive variables test, the LT and the DBT did not show any significant correlation with any piece. We started to think that those tests' ability of discriminating the students. We know that all the students in the LT appeared to be at the formal operational stage and did not make any

significant distinction among the students. In the same manners, DBT did appear not to be a good discriminator in terms of students' working memory capacities. A majority of the students' working memory capacities were either six or five. Maybe our students were really very alike in terms of the their cognitive developments and working memory capacities and therefore the standard deviations for those test appeared to be very low. Another reason for DBT to appear to be insignificant might be that working memory capacity may be irrelevant for the types of the problems used in the study.

Table 4.29
The Correlation Coefficients for the Cognitive Variables and the Pieces

		WEQ	BEQ	MP	EF	MF	LR	PY	MC	SR	MR
	N	17	17	17	17	17	17	17	17	17	17
TOLT	Correlation Coefficient	.414	.497(*)	.375	-.015	.302	.054	.175	.383	.302	.208
	Sig. (2-tailed)	.099	.042	.138	.956	.238	.836	.502	.129	.238	.423
DBT	Correlation Coefficient	-.189	.079	.025	.371	-.115	.003	.305	-.039	.191	-.115
	Sig. (2-tailed)	.468	.762	.923	.142	.660	.991	.234	.883	.463	.660
MCAT	Correlation Coefficient	.310	.508(*)	.557(*)	.096	.411	.383	.572(*)	.603(*)	.597(*)	.000
	Sig. (2-tailed)	.226	.037	.020	.714	.101	.130	.016	.010	.011	1.000
LT	Correlation Coefficient	-.024	.284	.432	.244	.414	-.029	-.080	.204	.242	.282
	Sig. (2-tailed)	.928	.269	.083	.345	.099	.912	.760	.432	.349	.273
BPCI	Correlation Coefficient	.488(*)	.640(**)	.288	-.417	.318	.080	.113	.336	.075	.468
	Sig. (2-tailed)	.047	.006	.263	.096	.214	.761	.667	.187	.775	.058

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Conclusion

The results revealed that successful students are more successful in linking the pieces (have a better conceptual understanding) and solving the problems than the unsuccessful students are. They, however, did not show significantly better performance on doing pieces (domain-specific knowledge) and solving exercises than unsuccessful counterparts did.

Successful students also appeared to be different in how they approach problems, what strategies they use, and in making fewer algorithmic mistakes when compared to unsuccessful students. Successful students, however, did not seem to be statistically significantly different from the unsuccessful students in terms of quantitatively tested cognitive abilities except formal (proportional) reasoning ability and in the understanding of mole concept.

Lastly, the investigation of the cognitive variables indicated that only formal (proportional) reasoning ability and understanding of mole concept are good predictors of students' success in stoichiometry. The other variables (working memory capacity, cognitive development, and understanding of particulate nature of matter), on other hand, appeared to have no significant influence on undergraduate students' achievements in solving stoichiometry problems. Although understanding of particulate nature of matter did not show correlation with success in solving general stoichiometry problems, it

interestingly showed statistically significant relation with writing and balancing chemical equations.

CHAPTER V

DISCUSSIONS AND CONCLUSIONS

In this chapter, the results of this study are discussed in the light of the previous research findings. We will also discuss the implications of our work for instructors of stoichiometry. The limitations to the study are presented as well, and recommendations for future research.

Comparison with Previous Research

As a reminder, consider again our three research questions:

(1) To what extent do the difficulties in solving stoichiometry problems stem from poor understanding of pieces (domain-specific knowledge) versus students' inability to link those pieces together (conceptual knowledge)?

(2) What are the differences between successful and unsuccessful students in knowledge, ability, and practice?

(3) What are the roles of cognitive development, formal (proportional) reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in successful and unsuccessful students' problem solving success in stoichiometry?

For the purposes of comparing our results with previous research, it is helpful to sub-divide each research question to better fit with the research base:

1. Pieces and Linking
    a. The nature of students' knowledge achievement with *pieces*
    b. Students' success with *linking*: Are our students conceptual or algorithmic problem solvers?
2. Differences between the *successful and unsuccessful* students in the view of prior research findings on *experts and novices*
    a. Knowledge differences
    b. Strategy differences
    c. Cognitive ability differences
3. Significance of several cognitive variables – do they correlate with success?
    a. Understanding of the mole concept (Mole Concept Achievement Test-MCAT)
    b. Formal (proportional) reasoning ability (Test of Logical Thinking-TOLT)
    c. Understanding of the particulate nature of matter (Berlin Particle Concept Inventory-BPCI)
    d. Working memory capacity (Digit Backwards Test-DBT)
    e. Cognitive development (Longeot Test-LT)

Pieces and Linking

There are two main goals aimed in science education. The first and most important one is that gaining of a body of knowledge, which is comprehensive, organized, and coherent. The other one is the ability to solve problems in the discipline by feeding the coherent conceptual knowledge with procedural knowledge (Gabel & Bunce, 1994; Heyworth, 1999; Lee et al., 2001). Nevertheless, our investigation of students' performances in solving stoichiometric problems indicated that the instructors in science have not satisfactorily achieved either of those goals. Although students showed comparatively better performance at solving exercises, the students in general were not very successful at solving stoichiometric problems, especially the complex ones. Students had great difficulty with stoichiometric problems as found in other studies (Boujaoude & Barakat, 2000; Huddle & Pillay, 1996; Schmidt, 1997; Schmidt & Jigneus, 2003).

The reasons behind the students' difficulties again were at the center of our attention. Many researchers have tried to diagnose the problem and find the sources of the difficulties (Camacho & Good, 1989; Gabel & Sherwood, 1983; Wolfer & Lederman, 2000). They conclude that the students' knowledge of chemistry is not at expected or desired level by chemistry educators. The problem is directly related to the ability of chemistry students to apply knowledge of chemistry in solving chemistry problems. We therefore

in the analysis of students' problem solving performances we give a special attention to the students' knowledge to identify the source of the difficulties that students encountered while solving the stoichiometry problems.

The Nature of Students' Knowledge Achievement with Pieces

Our analysis of the stoichiometric pieces (WEQ, BEQ, MP, EF, MF, PY, LR, MC, and SR) reveals that students are in general very good at doing the pieces although they occasionally make mistakes with the pieces. Students' good performances with pieces were proven by the high attempt success rates (ASR) as listed in the table 4.12. The lowest success rates belong to the EF and WEQ pieces but we do not worry too much about these two pieces because nomenclature hints for the WEQ resolve the problem and the EF was used just about two times in average, and is a minor topic in stoichiometry. Neither of these greatly affects students' success in solving stoichiometry problems. Overall, students have all the pieces necessary for solving the stoichiometry problems.

Consider Exercise 9 as evidence for us to believe that students have the pieces necessary even when solving problems that they find difficult. In the Exercise 9, after students read the question, ten of them did not consider the LR and they attempted to solve the problem without determining the LR. However, when we asked if they have heard the limiting reagent, all said

"yes" and realized that they made a mistake. They suddenly went back and solved the problem again considering the LR. More importantly, 60 % of them got the right LR.

This finding reminded me of an activity related to the thermal equilibrium which I have used when teaching prospective elementary teachers. In this activity, we give students a wooden and an iron block at the same time and we emphasize that both blocks have been kept in the same room for weeks. Later, we ask them if the blocks have the same temperature or one is colder than other one. They usually choose the iron block as the cold one because it feels cold to the touch. They forgot the fact that the objects, regardless of its material, after a while reach equilibrium in temperature. Further discussion reveals that they do have the knowledge about the thermal equilibrium, conductivity, the body's temperature (~98.6 F^0), and the room's temperature (~72 F^0), but they often cannot put these pieces together to bring a meaningful explanation.

These examples showed that the sources of the students' poor performances are not always related to students' misconceptions or poor understanding of the pieces. There are situations where students understood the pieces but cannot always retrieve those knowledge pieces or link them successfully to solve the problems or answer the questions.

Students' Success with Linking: Are Our Students Conceptual or Algorithmic Problem Solvers?

Although students are comparatively good at doing the pieces and applying their knowledge to the exercises, they could not apply their knowledge and put the pieces together to solve the problems successfully in general. After analyzing the pieces involved in stoichiometric questions, we investigated students' performance with 25 stoichiometry questions with varying difficulty levels. We found that almost all students showed poorer performance with solving questions, especially the complex problems, than they did show with the pieces. It was an important sign for us to believe that main source of the difficulty is students' inability to construct their knowledge by linking the pieces in a way that fits the physical representation of the problem and leads to a successful solution. This appears to be consistent with the findings in research in science education (Pasceralla, 2004; diSessa, 1988; Anderson, 1993; & Lee et al., 2001). Like these researchers we believe that students hold unconnected and fragmented conceptual and procedural knowledge of science and this situation causes students to have difficulty in applying what they have learned in science classes to solve problems in chemistry or other disciplines.

While searching the literature we found that there are many researchers who think the same way as we do but use different terms than

the ones we have used in this study. It appears that our Research Question #1 (pieces vs. linking) has much overlap with previous research that investigates *algorithmic* vs. *conceptual* problem solving. This body of literature also compares the students' success with pieces, exercises, and problems but they call those who are successful at doing exercises algorithmic problem solvers rather than simply stating that students are good at doing the pieces. In the same manner, they call those who are successful with the problems as conceptual problem solvers rather than simply saying that they are good at putting the pieces together. This research assumes that having good conceptual knowledge is synonymous with ability to link.

For example, Frazer and Sleet (1984) and Ashmore et al. (1979) break down the problems into the sub-problems (steps) and investigate how students succeed differently as they deal with the complete problems and with the corresponding sub-problems. They then categorize students according to their success with the complete and corresponding sub-problems. The students who are successful with both complete problems and corresponding sub-problems are named as successful (conceptual) problem solvers while the students who are successful with sub-problems but not with the complete problems are called unsuccessful (algorithmic) problem solvers.

It is perhaps useful to consider some examples of how conceptual understanding can be synonymous with the ability to link pieces. Recall that problem solving in chemistry requires many types of *conceptual*

understanding. For example, we know that success in chemistry problem solving demands a mental transfer between several modes of representations (Gabel, 1998). Having a good conceptual understanding of the different modes of representation (words, symbols, numbers, graphical models) for molecules *means* being able to, for example, go from reading a chemical name to writing a chemical equation (WEQ), balance it (BEQ), calculate the moles involved (MC), and find the amount of product produced (SR). Being able to do any *one* of those pieces would be an *algorithmic* ability. Seeing how they are connected demonstrates (what the literature calls) a *conceptual* understanding. Therefore, conceptual understanding is perceived as essential for solving stoichiometry problems (Boujaoude & Barakat, 2000). So, we can make sense of Frazer and Sleet's (1984) method of categorization of students. When students are classified as conceptual problem solvers they are able to see the linkage among the pieces (concepts) and be successful in putting them together. On the other hand, algorithmic problem solvers are unsuccessful at putting the pieces together because they lack conceptual understanding.

Another way that researchers use to identify algorithmic and conceptual problem solvers is using students' performance in questions demanding different amounts of mental space. This feature of the problem is called M-demand (Z-demand) and the number of steps is correlated with M-demand (Z-demand) (Tsaparlis et al., 1998: Tsaparlis & Angelopoulos, 2000; Niaz, 1988, 1989). It is assumed that problems with more steps have higher

M-demand and require more mental space. Tsaparlis et al. (1998), Tsaparlis & Angelopoulos (2000), and Niaz (1988, 1989) use a test including the questions with varying number of steps to be solved. In this method, researchers consider the students as algorithmic problem solvers when they are successful with the questions that have a few steps and demand low mental capacity (M-demand) and as conceptual problem solvers when they are successful with the questions, which have comparatively more steps and require higher M-demand. The number of steps in their questions reminded us the differences between the exercises and problems. Although, we do not believe that problems necessarily have to have more steps than the exercises (see Figure 4.21) but we know that in general exercises have simplistic and straightforward schemas compared to problems' complicated and nonlinear schemas (see Figures 4.20a and 4.20b). So, in this respect, the students who can solve the problems with complicated schemas (in our language, can "link" pieces) could be called conceptual problem solvers and the students who solve the exercises with the simple schemas are identified as algorithmic problem solvers.

Johnstone (2001) uses a similar classification but emphasizes on the interaction between the problem and the solver. If the solver knows how to solve the problem at the beginning, the problem is defined as a familiar problem (algorithmic problem) and students who are successful with that type of problem are introduced as algorithmic problem solvers. In contrast,

the problem whose solution is not known by the solver is identified as an unfamiliar problem (conceptual problem). So, in this respect, students who show good performance with that type of problem will be conceptual problem solvers. If we call the familiar questions "exercises" and unfamiliar questions "problems" then, based on the Hayes's (1981) definition, we see that there is no difference between Johnstone's classification of students and Tsaparlis et al.'s (1998).

All these classifications illuminate the importance of conceptual understanding. Therefore, instruction in science and other disciplines ought to motivate students to construct a conceptual understanding of scientific phenomena rather than applying algorithms to problems. Although many educators know this fact, they have not been satisfactorily successful at making their students' conceptual problem solvers. In many studies, students' conceptual and algorithmic problem solving abilities are investigated and compared (Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nakhleh et al., 1996; Herron & Greenbowe, 1986; Nurrenbern & Pickering, 1987; Sawrey, 1990; Chiu, 2001). The common findings of all these studies are that students are better algorithmic problem solvers and there is a gap between students' conceptual and algorithmic problem solving abilities and successes. These findings are saddening if we really see the difference between students' conceptual and algorithmic problem solving achievements

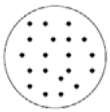
as a gap. But one can also see that discrepancy as the distance that can be closed (Niaz, 1994).

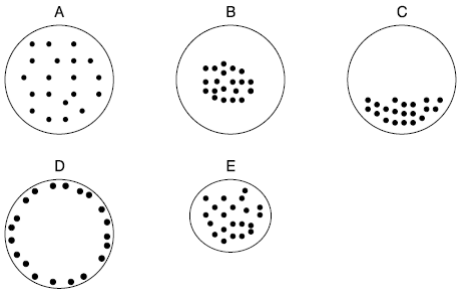
Niaz (1994) interprets the gap between the students' conceptual and algorithmic problem solving performances as continuum along which algorithmic problem solvers become conceptual problem solvers as they progress. I see the great parallelism between Niaz's view of transformation of students from algorithmic problem solvers into conceptual problem solvers and diSessa's view of transformation of novices into experts and his description of learning.

diSessa (1988) defines learning mainly as restructuring existing knowledge pieces into a more coherent knowledge system in students' minds, which eventually results in a better conceptual knowledge. For instance, to change the concepts of students who give wrong accounts for why metals feel colder than the wood block, which are sitting in the same room for a long time we could help them use the knowledge pieces they have about body temperature and conductivity. If these pieces already exist in their minds, it might be more effective to build on them than to try to replace students' old knowledge pieces with new ones. What students usually need is to link their existing knowledge pieces in suitable ways to associate them properly, construct new knowledge structures, and make meaningful explanations based on their new knowledge structures.

In both Niaz's and diSessa's explanations, the common point is that there is an evolution in students' and novices' knowledge and naturally their problem solving performances. As students have more organized and a better conceptual knowledge, they solve the problems more successfully, become more conceptual problem solvers, and eventually turn to be experts. Although we believe that the novices will eventually transform into experts, it is going to take a lot of time and effort. Until then we might expect to see that novices will tend to solve the problems mostly relying on algorithm and be more successful with algorithmic problems than the conceptual problems.

One characteristic of algorithmic problem solving is an over-reliance on mathematical formulas, even for questions that can be solved without mathematics. Consider one example which is used in many studies to investigate the students' conceptual and algorithmic problem solving achievements (Nakhleh, 1993; Nakhleh & Mitchell, 1993; BouJaoude et al., 2004). The question is excerpted from the Nakhleh's study (1993, p.52):

> The following diagram represents a cross sectional area of a rigid sealed tank filled with hydrogen gas at 20°C, at 3 atm pressure. The dots represent the distribution of all the hydrogen molecules in the tank.
>
> 
>
> Which of the following diagrams illustrate one probable distribution of molecules of Hydrogen Gas in the sealed tank if the temperature is lowered to – 5°C? (The boiling point of Hydrogen is – 252°C)



In the examination of students' of this question and such others, researchers conclude that students tend to use the algorithm to solve the problems and they are not very successful at solving these kinds of conceptual questions about not only the gases but also limiting reagent, empirical formulas, and density (Nakhleh, 1993). Most students while answering this question do a common mistake as the students do while explaining the formation of seasons or solving the questions involved the limiting reagent. They do not use important pieces of information while making judgments and explanations. For instance in this question students forget the fact that gases always fill the container in which they are placed, which is an important attribute of the gases. Although most students know this fact from their classes and everyday experiences, they ignore or do not consider it and simply depend on the algorithm. They use the ideal gas equation (PV=nRT) and conclude that if the T goes down V should get smaller. As a result, they choose one of the incorrect answers.

The students' answers and explanations for this question and their attributes in limiting reagent problems illuminate that students often do not

have conceptual understanding of the concepts, This means that the learner's knowledge is not organized properly to ease the task of problem solving and increase the success in solving problems. Unsuccessful students tend to use algorithmic methods because the formulas and equations are stored as individual pieces in their minds (e.g. ideal gas equation, concentration formula, density formula) as unconnected facts devoid of the concepts they should normally be attached to.

In conclusion, we say that our findings are consistent with previous research showing that students do not do well on complex problems, in part, because they cannot link the pieces necessary. They cannot link the pieces because they do not have well-organized and connected domain-specific knowledge.

Differences between the Successful and Unsuccessful Students in the View of Prior Research Findings on Experts and Novices

We observed many differences between attributes of successful and unsuccessful students regarding their conceptual knowledge, procedural knowledge (strategies), and cognitive variables such as formal (proportional) reasoning abilities, working memory capacities, and cognitive developments. Some of those differences were statistically significant and some of them were not. In this section, we are going to look over the differences between

successful and unsuccessful students and try to make sense of them in view of the differences between experts and novices cited in the literature and discussion made in the previous section regarding first research question.

Knowledge Differences

Many researchers (Lee et al. 2001; Chandran, et al., 1987; Nakhleh & Mitchell, 1993; BouJaoude & Barakat, 2003; Gabel & Bunce, 1994; Johnstone, 2001) believe that students' knowledge (i.e. factual knowledge) is an important factor influencing students' success in solving problems in chemistry and in other disciplines. Indeed, we do find a small, but significant difference between the successful and unsuccessful students' ability on stoichiometric knowledge pieces.

The analysis of students' knowledge pieces revealed that successful students in our sample appeared to be statistically more successful than unsuccessful ones for only two pieces (based on the independent t-test results). This also is similar to other studies , which reveal that experts have a more comprehensive network of knowledge of basic facts than novices do (Heyworth, 1999; Gerace, 2003; Bedard & Chi, 1992). It is understood, however, that novices have a poor *understanding* of formulae, whereas experts' knowledge is accurate and linked to underlying procedural knowledge.

One consequence of the smallness of the difference between the successful and unsuccessful students' factual knowledge was the very similar performance in doing exercises. As the difficulty of problems increased, however, the differences between the students grew. This is consistent with previous findings which show that novices cannot engage in qualitative analysis of the problems prior to working with equations. Unsuccessful students do not have appropriate principle-oriented knowledge structure like experts do (Breslow, 2001; Marshall, 2003; Perkins & Salomon, 1989).

The knowledge of all the necessary pieces is not enough when there is a need to see the big picture. Experts are able to sift through detailed situations to pick out those pieces which are relevant to the solution. On other hand, novices' schema may contain sufficiently elaborate factual knowledge but they are unconnected from the related principles and cannot, therefore filter out unnecessary information. For example, consider the following problem.

> A fuel mixture used in early days of rocketry is composed of two liquids. Hydrazine (N_2H_4) and dinitrogen tetraoxide (N_2O_4), which ignite on contact to form nitrogen gas and water vapor. How many grams of nitrogen gas form when 100g of N_2H_4 and 200g of N_2O_4 are mixed (Silberberg, 2006, p.113)?

When novices focus on the details or unnecessary information for the solution too much and they cannot see the question as a limiting reagent question. Therefore, they forget to determine the limiting reagent and solve the problem without considering the limiting reagent. On the contrary, experts

when they see this question, they quickly recognize the type of question and classify it according to underlying principle.

Strategy Differences

Our results show that successful students mostly preferred working-forward method while unsuccessful students tended to use means-ends analysis. These selections make sense when we consider previous findings regarding the behaviors of experts and novices.

Experts have much more power to think in advance and plan strategies than novices do because experts are able to recall a group of knowledge pieces collected around the principles at a time rather than thinking about each piece separately (Perkins & Salomon, 1989). They, more importantly, have an extensive organized knowledge base formed by domain-specific patterns, which leads to quick recognition of patterns in the questions and promotes *forward reasoning* that moves from the givens in the question directly toward a solution and, finally, an answer (Perkins & Salomon, 1989; Breslow, 2001).

In contrast, novices tend to use backward reasoning (means-ends analysis) (Perkins & Salomon, 1989). This backward reasoning differs from the experts' forward reasoning in terms of its direction. Novices focus first on unknowns in the question and then givens and finally look for a formula or

an equation to solve problems. After deciding on a formula and an equation and determining the givens, novices plug in numbers in order to find the unknowns. The other important difference between novices and experts is that novices cannot recall the knowledge pieces as a group as experts do and have to deal with the pieces individually. They tend to emphasize on superficial features of the problems and memorize them and apply them to different problems without worrying the context and other aspects of the problems (Wenning, 2003; Perkins & Salomon, 1989).

The strategic differences between novices and experts and between successful and unsuccessful students are usually clear but there are certain circumstances in which those differences become minor and insignificant and experts and novices show similar characteristics (Larkin et al., 1980). In the study, we observed such cases while students attempt to solve the complex problems. Successful students (experts) like unsuccessful students (novices) tend to use means-ends analysis when they encounter a true problem. They, however, followed this strategy more efficiently than unsuccessful students did.

Cognitive Ability Differences

In this study, we also found the differences among the successful and unsuccessful students' cognitive differences. These cognitive variables include

students' formal (proportional) reasoning abilities, cognitive development, working memory capacity, conceptual understanding of mole concept and particulate nature of matter. The results revealed that the only significant differences were observed between the successful and unsuccessful students' TOLT and MCAT scores, which were representing the formal (proportional) reasoning ability and conceptual understanding of mole concept, respectively. We however could not find any research literature that employed these tests for the same reason to compare our findings to others. There were studies that either focused on other attributes of successful and unsuccessful students or used the tests for the whole sample of students without categorizing the students as successful and unsuccessful or as experts and novices. We therefore extensively talk about the cognitive variables and the tests, which measure the each variable in a different context in the next section without worrying about the differences between successful and unsuccessful students.

Significance of Several Cognitive Variables: Do They Correlate with Success?

As we analyzed the students problem solving performances we were better understanding that the problem solving is indeed very complicated and challenging task to do. The success in problem solving depends on many variables. Therefore, the research on problem solving demands innovative

designs, careful data collection, and meticulous analysis of the data. Considering these facts, we wanted to explore the effects of as many variables as we could on problem solving in order to have a better understanding of the complex process of problem solving.

In the first section, we checked our data from the questions' perspective without grouping students and without worrying who was solving the problem. We tried to focus on the knowledge and problem solving performances of all the students. In the second section, we examined the data from the students' perspective and found the differences between the successful and unsuccessful students. Finally, in the third and last section, we wanted to look at the data from the perspective of cognitive variables and investigate the effects of cognitive variables on students' performances in stoichiometric problem solving if any existed.

The analysis of the cognitive variables revealed that three of the five cognitive variables, formal (proportional) reasoning ability, conceptual understanding of particle model and mole concept have been found to be significant in predicting students' problem solving performances in stoichiometry with MCAT being the most significant. Chandran et al (1987) did a similar research to find out if there are correlations between their variables, prior knowledge, formal reasoning ability, field dependence/independence, and memory capacity. They also found statistically significant correlations between formal reasoning and prior

knowledge and variations in chemistry achievement. In their research, memory capacity (measured by FIT- Figural Intersection Test) also did not show significant role in chemistry achievement.

Understanding of the Mole Concept (Mole Concept Achievement Test -MCAT)

The conceptual understanding of the mole concept appeared to be statistically most significant variable affecting the students' success in stoichiometric problem solving. We measured students' understanding of mole concept using the MCAT, which was developed and used by a group of researchers to identify students' abilities and knowledge related to mole concept and meaning of the subscripts in the chemical formulas (Gower et al., 1977; Griffiths, Kass, & Cornish, 1983; Friedel & Maloney, 1992).

Previous researchers simply employed the MCAT as a stand-alone test to examine the students' understanding of the mole concept and subscripts. In this study used this test to search for a correlation of understanding of the mole concept with students' problem solving performance in stoichiometry. It is therefore difficult to compare our findings to the findings of others. Still, we know that many researchers stressed on the importance of mole concept for the success in chemistry ((Duncan & Johnstone, 1973; Furio *et al.*, 2002; Furio & Guisasola, 2000; Krishnan, 1994; Larson, 1997); Kolb , 1978). The very high significant correlation coefficient ($r=.914$, $p<.01$) between the

students MCAT scores and the TSRs (total success rates) once again revealed the importance of mole concept for stoichiometric problem solving and for success in chemistry.

Formal (Proportional) Reasoning Ability (Test of Logical Thinking-TOLT)

Our second cognitive variable showing the statistically significant correlation with the students' problem solving performances in stoichiometry was the formal reasoning ability, which was measured by the TOLT. We did find a significant correlation between students' TOLT scores and their performances in stoichiometric problem solving. This is consistent with other researchers who have found the formal reasoning ability measured by the TOLT to be a good predictor of chemistry achievement (Sanchez & Betkouski, 1986; Trifone, 1987; Lawson and Renner, 1975).

It is interesting to note that the TOLT scores do not correlate with the attempt success rates (ASRs) for the stoichiometric ratio (SR) piece. This is peculiar as the TOLT is designed to measure a combination of all different reasoning abilities *including* the students' proportional reasoning ability. Proportional reasoning ability is seen as crucial for students to be successful in chemistry topics such as stoichiometry and gas laws where quantitative aspect of science becomes important and in which ratios are used (Chandran et al., 1987). We can only speculate that, because the TOLT has just two

questions targeted at measuring proportional reasoning, it is not valid to use the overall TOLT score as a proxy for proportional reasoning ability.

Understanding of the Particulate Nature of Matter (Berlin Particle Concept Inventory-BPCI)

The understanding of the particulate nature of matter was the third and the last statistically significant cognitive variable, which was measured by the BPCI. The correlation for the BPCI scores was different from that of other two significant variables. The other two variables, formal reasoning ability and the understanding of mole concept, were significantly correlated with the students total success rates representing their performance in problem solving but the BPCI scores did not show significant correlation with the students' total success rates. Rather, they showed significant correlation with the WEQ and BEQ pieces. It appeared that the understanding of particulate nature of matter is important to be successful in writing chemical equations ($r=.49$, $p<.05$) and balancing them ($r=.64$, $p<.01$).

This finding seemed consistent with other researchers' perceptions and findings. Many educators (Gabel & Bunce, 1994; Nakhleh, 1992; Wolfer & Lederman, 2000) have suggested that students' lack of understanding of the particulate nature of matter makes solving problems difficult, especially the problems involving chemical reactions and gas laws. For the relation between

the stoichiometry and particulate nature of matter, Gabel & Bunce (1994) state that some problems in stoichiometry can be solved without comprehending particulate nature of matter but a good understanding of the particle model can help students grasp the chemical reactions and appreciate the quantitative relationships among the substances involved in reactions.

Working Memory Capacity (Digit Backwards Test-DBT)

The working memory capacity is our fourth cognitive variable in the study and one of the two statistically insignificant variables. When we did not see the significant correlations between the DBT scores and the students' total success rates, we did not get surprised very much. We knew that there are some studies (Johnstone & El-Banna, 1986) in which students' working memory capacities show the significant correlation with students' achievement in chemistry and there are some studies (Opdenacker et al., 1990; Chandran, 1987) in which the DBT score were not significantly correlated with the students' achievements in chemistry.

Our findings were consistent with the findings of Opdenacker et al. (1990). The highest, lowest, and the average working memory capacities of the students in our study are 8, 3, and 5.6, respectively. In Opdenacker et al.'s (1990) study, the highest and lowest numbers are also 8 and 3 but average working memory capacity showed little difference, which was found

to be 5.3. Additionally, Opdenacker et al. (1990) do not find a significant relationship between students' working memory capacity and problem solving performance on chemistry placement tests or other subject placement tests. Our results showed a great parallelism with the Opdenacker et al's (1990) but they were quite different from the findings of Johnstone & El-Banna (1986).

Johnstone and El-Banna's (1986) study claims that there is a significant correlation between working memory capacity and students' performance in solving chemical problems. Johnstone and El-Banna's (1986) study differs from Opdenacker at al.'s (1990) and ours mainly in that it examines the students' performance related to the M-demand of the problems. They first determine the M-demand of the questions and group them. Then, they investigate the relation between the students' working memory capacities and success in solving the problems, which demand different amount of mental capacity. In their study, they found significant relationship between students' varying working memory capacities and M-demand of the problems. Although the students who have higher working memory capacities appear to be more successful with the problems having high M-demands, we think the results are not very reliable because of the process of determination of M-demands of the problems. Determining the M-demands of the problems is challenging and might be misleading. M-demand is defined as a function of the number of thought steps and naturally, it is

difficult for experts who determine the M-demand of the problems, to know what steps will be taken by novices (students).

As we mentioned, our results are different from Johnstone and El-Banna (1986). We did not observe a significant correlation between students' success in stoichiometric problem solving and working memory capacity. We believe that the lack of any observed relationship, in our study, between memory capacity and the achievement in chemistry could also be due to the lack of variation in students' performance in the DBT scores (Chandran et al. 1987). Most students obtained a score of 5 or 6 and the standard deviation was relatively small. In this limited range, DBT scores therefore might not appear to be statistically significantly related to achievement in stoichiometry.

Cognitive Development (Longeot Test-LT)

The cognitive development is the last cognitive variable in the study and one of the two variables, which did not show significant correlation with the students' success in stoichiometry. We employed the LT to measure the students' cognitive developments and investigate its relation to the students' success in stoichiometric problem solving. The LT scores did not significantly correlate with the students' success in stoichiometry. These results made sense when we see the scores. The average percent rate was 81.5 and

standard deviation was very low. All students appeared to be at formal operational stage, which means they can deal with the abstract concepts. Therefore, we cannot use the students' cognitive development to predict their success in stoichiometry or chemistry.

We looked at other studies to interpret our data better but we could not find a similar study done before in terms of design, the use of LT, and types of the students. That is important to point that there are very few studies used the LT for undergraduates. It is mostly used to measure secondary students' cognitive developments. Moreover, the studies measuring the cognitive developments of undergraduates and its influence on achievement in chemistry do not usually employ the LT.

Sheehan (1970) found the influence of instruction in science on the group of students, which were determined using the results of LT test. He chose his students from the grade 4 to 9. Smith and Van Egeren (1977) did a very similar study but investigated high school students' success in chemistry classrooms. Like Smith and Van Egeren (1977), Gabel and Sherwood (1979) did a study choosing their students among high school students but Gabel and Sherwood (1979) differently focused on students' success in ACS and NSTA chemistry achievement exams rather than focusing a single topic. They found that some of their students were at formal level and some were at concrete level. The comparing the students' cognitive developments and their

ACS scores revealed that the students at formal formal-operational level had better scores.

Pandey et al. (1993) and Farmer et al. (1982) also chose their subject among high school students. Pandey et al (1993) did a study in India to find out the students' cognitive development levels in different grades using the LT. Students in their study aged from 13 to 19. They found that with increases in age the percentage of students at the concrete operational stage decreases while at the formal operational stage the number decreases. Their results showed that 83.84% of students are at concrete operational stage and the rest were at the formal operational stage at grade 9 while 48.79% of students at concrete operational stage and the rest were at the formal operational stage at grade twelve.

On the other hand, Farmer et al. (1982) employed three different methods to measure the students' cognitive developments through different techniques and obtain healthier information about their cognitive stages. One of the methods was the use of the LT. According to LT results, the percentages of students at concrete operation and formal operational stages appeared to be 34.4% and 65.6%, respectively. They did not represent the data according to grades but gave it as a whole. Their sample included 607 ninth and tenth graders and a few eleventh and twelfth graders (numbers were not identified in the research).

Only one study (Ward et al. (1981)) included undergraduate chemistry students. Although Ward et al. (1981) used the LT in the study, they did not search for a correlation with students' success in any chemical topic or chemistry at all. They simply investigated the reliability of the LT itself, they found it reliable. In Ward et al.'s (1981) study, 209 chemistry students participated. 130 students were chosen among the students taking Chemistry 116. This is curious because we also chose our students among those who were taking Chemistry 116 at another campus of the same university. Ward et al found that only 5.75 % of their students at the concrete operational level with the remainder at the formal operational level. This is similar to our findings in which no student among our subjects was at the concrete operational level – all appeared to be at the formal operational level. As this difference (0% vs. 5.75%) is small, we can conclude that there was not a significant difference between Ward et al.'s findings and ours.

Implications for Classroom Instruction

Although there is some overlap, we find it useful to organize our discussion of teaching implications around the three research questions. In light of the first research question, we will discuss effective techniques to teach more conceptually and make the students conceptual learners. The second research question discussion will focus on what could be helpful for

bringing unsuccessful problem solvers up to the level of successful problem solvers. The third question discussion reveals the need to develop more materials appropriate for students' formal (proportional) reasoning abilities or to develop activities nourish students' proportional reasoning abilities.

Considering the Findings of the First Research Question

The analysis of the data of the first question reveal that the main problem is the students' inability to link the necessary pieces successfully for solving stoichiometric problem solving, which means students' conceptual knowledge is problematic and not good enough for solving complex problems. Therefore, educators should target students' knowledge base and provide students the means necessary to develop their knowledge into a more coherent, connected, hierarchical form. Knowledge that is organized hierarchically is used more efficiently and facilitates the recall of the pieces already stored (Pasceralla, 2002). Below are some specific techniques an instructor of stoichiometry could consider to develop this connected knowledge.

Instructors should explicitly discuss the linkage concepts(Wolfer & Lederman, 2000). For example, when teaching about limiting reagent problems, the instructor could point out how the problem requires writing equation (WEQ), balancing equation (BEQ), mole concept (MC),

stoichiometric ratio (SR), and the limiting reagent (LR) piece be linked. As another example, throughout a General Chemistry course the instructor can discuss how the particle nature of matter "makes sense" in multiple contexts (i.e. can be connected to many situations): macroscopic observations, theoretical explanations, microscopic level graphical depictions, and symbolic representations.

Assessments should also be changed in a way that values and rewards conceptual understanding in addition to algorithmic problem solving (BouJaoude & Barakat, 2000). If students realize that, their teachers value meaningful learning (conceptual understanding) more than route memorization of the rules or facts, students will more likely be motivated to learn the concepts rather than formulas. Students will know that the quality of explanations will be at the center of the learning and the assessment and their instructors are not seeking just a quantitative answer but also corresponding explanation (BouJaoude & Barakat, 2000). The way the assessment are designed and prepared can encourage students to focus more on concepts than simple facts and inquire about the interrelations among the those concepts which is the fundamental for conceptual understanding and a very important prerequisite for successful problem solving (BouJaoude & Barakat, 2003).

Some studies suggest that inquiry-based learning is more effective for generating organized conceptual knowledge. Examples include student-

centered teaching practices such as the Process Oriented Guided Inquiry Learning project (www.pogil.org) and similar techniques of splitting the class into small groups (Nakhleh et al., 1996; Phelps, 1996; BouJaoude & Barakat, 2003; Huddle & Pillay, 1996; Bergquist and Heikkinen, 1990).

Other possibly useful (although not tested in the literature) to promote conceptual understanding and linking the pieces include the following methods:

- More time could be spent on complex problems than individual pieces in stoichiometry. Instructors could spend more time to developing the ability of linking pieces through doing complex problems.
- Start by teaching complex problems first and, then, dissecting the problems to find out what pieces are required. The idea behind it resembles doing puzzles.
- Since it is likely that some instructors will insist on teaching pieces first, it could be helpful for them to progress gradually from simple to complex problems. When instructors finish teaching first and second pieces they could give the problems involving the first and second piece and when they finish third piece they could give problems involving first three pieces and so on. This method might also protect students from feeling

frustrated with end of chapter problems that involve many pieces.

- One last strategy is to assign the homework questions as a set of mixed problems rather than as categorized questions under certain pieces and concepts. This method may not help students see the connections but avoid them from compartmentalizing their knowledge pieces.

Considering the Findings of the Second Research Question

The results of our study revealed that successful students are better than are unsuccessful counterparts in terms of not only the declarative (conceptual) knowledge but also procedural (operational) knowledge. In both types of the knowledge, successful students appear to be superior to the unsuccessful students. In research on problem solving, there are many studies aiming at transforming unsuccessful problem solvers (novices) into successful ones (experts) and increase their problem solving performance. To achieve this goal, researchers have done several studies (Woods, 1989; Stiff, 1988; Phelps, 1996; Bunce & Heikkinen, 1986; Asieba & Egbugara, 1993). These studies mainly can be collected under three categories: (1) the studies (Phelps, 1996), which focus on teaching *content* (declarative knowledge) conceptually for promoting problem solving, (2) the studies (Whimbey, 1984),

which emphasize on teaching *strategies* (procedural knowledge) to facilitate students' problem solving, and (3) others (Asieba & Egbugara, 1993) studies which stress on teaching both content (declarative knowledge) and strategies (procedural knowledge) at the same time to increase pupil's problem solving achievement. Although we believe that the studies in third group are the most effective and successful ones in terms of helping unsuccessful students, we in the following paragraphs, describe what the studies in all groups mean for teaching and learning.

Enriching Conceptual Understanding (declarative knowledge) for Successful Problem Solving

Researchers benefited from different techniques to improve students' conceptual understanding of subject matter. Robinson and Niaz (1991) compared the traditional and interactive technique (inquiry based teaching). In the interactive technique, they benefit from inquiry-based teaching techniques to supply the opportunities for students to involve actively in concept development and problem solving. For example, when teachers do a demonstration, they should have students bring an explanation before they themselves do so. They found that students in treatment group were more successful in solving stoichiometric problems than students who were taught by traditional lectures in control group.

In a similar way but using a different technique, Phelps (1996) compares the traditional (lectures) to the conceptual-focus technique. In her study, she examines how teaching, which emphasizes on conceptual aspects of chemistry, affects students' problem solving performance. In the experimental group, teacher uses conceptual questions or demonstrations, which demand conceptual explanations. They try to avoid questions that include numbers, which frequently can be solved by calculations. For instance, in this conceptual-focus technique, teachers show students two flasks, one filled with water and one filled with salt-water mixture. Then they shake both flasks at the same time. At the end, they ask students to explain the decrease in the volume of water in the flask containing salt-water mixture. Phelps finds that using a conceptual focus for the chemistry courses had many positive results for the students. In addition, she asserts that her students in her class indicated more enthusiasm for learning chemistry after they get used to the new conceptual approach.

Teaching Merely Strategies (procedural knowledge) for Problem Solving

In teaching problem solving strategies, researchers have employed instructional techniques such as solving problems with students' input and directions (Woods, 1989; Frank, Baker & Herron, 1987) and think aloud problem solving (Whimbey, 1984) to increase student's problem solving

achievement. In the former method, the instructor pretends that he does not know what to do next and waits for the commands from the students before he does anything or solves the problem the way he used to solve. In this method, students might see that problem solving involve uncertainty and confusion. More importantly, students witness that the teachers might struggle and have difficulties while solving the questions but they usually know how to surmount of these difficulties and work more systematically. In the latter method, class is split into groups, which have two students, and these students are asked to solve problems by thinking aloud and listen each other in turn. Students constantly alter their roles and they become listener and solver. Students benefit from this technique by seeing and learning other strategies used to solve problems by their peers and possible mistakes they can do. These researchers claimed that research results in increasing students' problem solving performance in terms of correct answer.

Although problem solver may benefit from these problem solving exercises in terms of developing strategies, we do not think that these methods are significantly effective in changing students' conceptual understanding and naturally their problem solving performance. Therefore, we think that it is important to develop and use methods targeting students' both declarative and procedural knowledge to get the optimum results.

Presenting both Variables: Conceptual Understanding (Declarative Knowledge) and Strategies (Procedural Knowledge)

One important mission for teachers is to help their students to develop conceptual understanding and problem solving skills (Lyle & Robinson, 2001). Several researchers have models of how this can be successful.

Asieba and Egbugara (1993) attempted to develop both students' conceptual understanding and problem solving skills and measured how this affected students' achievement. The research showed that students who were taught to achieve mastery of both the problem solving strategies (procedural knowledge) and content (declarative knowledge) did better than those who were taught to gain mastery of declarative knowledge with the exposition of procedural knowledge or procedural knowledge with the exposition of the declarative knowledge. There are more research pieces (Towns & Grant, 1998; Ross & Fulton, 1994; Staver, 1995), which examined the influence of both strategies and domain-specific knowledge at the same time on students' problem solving performance. They also reported that this technique positively affect students' attitudes and learning styles.

Ultimately, however, we need to be aware that attempting to teach problem solving does not directly teach *insight* (Johnstone, 2001). I believe that we can teach techniques that will help to organize the problem solving process and we can help students to store and organize their knowledge in

such a way as to facilitate problem solving. We hope that this will indirectly lead to insight, which is the ultimate key to real problem solving.

Considering the Findings for the Third Research Question

The findings revealed that students' success in stoichiometric problem solving was correlated with three of the five cognitive variables, formal (proportional) reasoning ability and understanding of mole concept and particulate nature of matter. Moreover, we found that successful students are better than are unsuccessful students in terms of conceptual understanding of mole concept and particle model and formal reasoning abilities. We have already talked about the implications related to conceptual understanding of mole concept and particulate nature of matter. Therefore, in this part, only the implications of students' formal reasoning ability on success in chemistry are discussed.

Research reveals that formal reasoning ability of learners correlates with students' achievement in chemistry (Huddle & Pillay, 1996). Studies emphasize that students need to have a good level of abstract thinking in order to understand some chemistry concepts such as mole concept, particulate nature of matter, meaning of chemical equations and make connections among three different levels of chemistry knowledge which leads success in problem solving (Boujaoude et al., 2004; BouJaoude & Barakat,

2003). Students who lack of proper formal reasoning ability or have low level of abstract thinking may benefit more and have higher achievement if the abstract concepts in chemistry are introduced in a concrete way especially considering the fact that formal reasoning ability of students may not increase greatly within the period of school year. Lovell (1961) and Lawson (1979) assert that instruction becomes more efficient when the developmental level of the learners are considered. Moreover, studies have evidenced that students can achieve at a higher level with the assistance of concrete exemplars of abstract concepts (Herron, 1975). The use of concrete exemplars may not, however, be always promising in increasing the students' achievement. Different techniques might be employed for those who have lower levels of formal reasoning ability.

Herron (1978) believes that use of concrete models, illustrations and diagrams can facilitate the understanding of abstract concepts and help students who lack of formal reasoning ability. Molecular models (Gable & Sherwood, 1984), illustrations (Cantu & Herron, 1978), pictorial representations (maps) for the solution of typical stoichiometry problems (Ault, 2001), models of physical processes (Howe & Durr, 1982), computerized instruction with more visual materials (Yalcinalp et al., 1995) have all been proved efficacious in improving students' achievement in chemistry. One final effective but different technique might be the use of cognitive conflict.

Students can be challenged by cognitive conflicts to facilitate their development of the correct reasoning ability (Trifone, 1987)

Conclusion

Being successful in problem solving in stoichiometry requires many abilities. An extensive organized domain-specific knowledge, formal reasoning ability, a good understanding of mole concept and particulate nature of matter, and a repertoire of decision-making mechanisms are necessary but not sufficient for successful problem solving. The problem solver must also construct some decision mechanism to select from among the available heuristics, or to develop new ones, as problem situations are faced.

People, who drive car, should be familiar with the problems related to cars. The gas is important for their cars but it means nothing when there is a problem with the engine of the car, or vice versa. To drive their cars safely and efficiently not only their cars need a good engine and gas, but also they need to take care of all other parts of their cars such as tires and fluids. Here, we can say that one of those factors is more important than other factors but it is clear that a lack of one of those necessities will make them walk. This metaphor is a nice example to understand the complexity of problem solving process, difficulty of teaching problem solving, and challenge of doing research on problem solving.

It seems that in problem solving area, there is still a great need for innovative studies to reveal the secret of mysterious problem solving process. If we accept the premise that good problem solvers are made and not born and if we believe that we have a responsibility to instruct in this area as well as in content, then we should do more research in this field to find out more about requirements for effective problem solving and help novices be better problem solvers.

Contributions to the Field

We believe this investigation contributed to the studies in the area of problem solving in chemistry in a few ways, which can be highlighted as follows:

- We have documented how the context of stoichiometry problem has a significant influence on the extent to which students can successfully complete pieces of the problem.
- Problem solving in stoichiometry, which is one of the common problem areas in general chemistry, was examined opposed to majority of studies, which focused on other general chemistry topics.
- The study employed both qualitative and quantitative methods to get better understanding of the differences between successful

and unsuccessful students as opposed to majority of studies, which utilize either one.

- The high number of variables was simultaneously considered to better analyze students' problem solving performances.
- The insignificant influence of working memory capacity, cognitive development and understanding of particulate nature of matter on problem solving performance in stoichiometry at undergraduate level were illuminated.

Limitations to the Study

There were a few limitations to this study. In this section, we will describe the ones that we were aware of.

In this study we were working with a small number of subjects: just nine successful and eight unsuccessful non-major undergraduate students. A larger sample of students might have revealed more statistically significant phenomena which are only apparent with large numbers. Still, given the large amount of qualitative data (especially transcripts of the think-aloud protocols), we believe that seventeen subjects was appropriate.

Another limitation is the inability to identify all "problems" as true problem (vs. exercises) for all students. As we mentioned earlier, status of a problem is not an innate characteristic of a question; rather it is a subtle

interaction between the question and the individual trying to answer the question (Bodner, 1987). Hence, our questions could be a real problem to the unsuccessful students and an exercise to the successful students. In this case, we cannot say that we investigated the differences between problem solving behaviors of successful and those of unsuccessful students.

It is impossible to say definitively that we have controlled for or observed all relevant variables effecting problem solving performance. We aimed to look at those several variables which we thought would be most important (e.g. cognitive development, working memory capacity, etc.). We knew that there were other variables, however, which might significantly influence subjects' problem solving achievement such as students' type of intelligence (Gardner, 1983) and their ability to construct the mental representations of the chemical changes (Stieff, 2004). These other factors could be as important as the ones that we studied, but our data does not speak to them one way or the other.

Another limitation was the researcher's bias. Going into the study we expected that domain specific knowledge was important and that students' conceptual knowledge structure was the most important for problem solving. Our interpretation of results could be affected by this thinking and could involve bias.

The last two limitations (difficulties) we noticed were about coding the think-aloud protocol data. We analyzed the students' solutions based on our

solution, which might be accepted as most common or traditional method to solve the problem. We had certain types and number of pieces in our solution but students sometimes used unconventional methods, which were different from the ones we used, to solve the problems. In these cases, naturally the pieces in terms of numbers and types were different. These discrepancies made the analysis challenging. Secondly, while assigning the codes to the pieces done by students occasionally we could not easily decide whether to assign a code of DD or CD. This ambiguity arises because it is sometimes hard to know if student did not do a piece because he or she did not know that piece needed to be done or because he/she simply could not do it. These difficulties introduced some measure of subjectivity into assigning codes and we could not escape the necessity to make inferences regarding what students were thinking.

Recommendations for Future Research

As we found some answers for our questions in the study, we saw that new questions arose during and after the study, too. Some of the questions related to the limitations and some of them related to the implications for teaching. We think all these questions are worthwhile considering for future research.

We believe it is worth doing new research with more students to investigate the influence of cognitive variables, especially the working memory capacity of students and cognitive development, on solving stoichiometric problem solving. In this test, we used the just one test for each variable. In a new research, along with the DBT and LT tests, the other tests for the same purpose can be used to have multiple data pieces on the same cognitive variables.

The investigation of students' linking ability in other topics and contexts might be another research topic. In this study, we examined the students' stoichiometric pieces and their abilities to connect them. In the new studies, the students' ability of linking can be investigated in other general chemistry topics such as gases and chemical equilibrium. A new version of the study can be designed to find out how students are successful in connecting the concepts learned in general chemistry to the concepts learned in further years in organic chemistry, physical chemistry or inorganic chemistry.

Future studies might also focus on the effect of different instructional techniques on improving students' conceptual understanding and abilities of linking pieces. Influence of inquiry-based teaching on students' success in solving stoichiometric problem solving might be investigated at different levels. The performance of students who receive traditional education in solving stoichiometric problems can be compared to that of students who

have inquiry-based education. Effects of teaching backward (introducing whole picture FIRST or complex problems) could be investigated.

A final study can be done related to the codes, which were generated and used only in this study. Although we calculated the reliability of the codes using the Kappa coefficient and found them to be reliable, we did not do anything to validate the codes. A study can be done to investigate the validity of the codes as well as develop an analysis scheme to be used in other studies. More research is needed to improve the validity of the codes and the generalizability with respect to other types of students and problems.

Appendix A

Human Subjects Institutional Review Board Approval

WESTERN MICHIGAN UNIVERSITY

Human Subjects Institutional Review Board

Date: December 16, 2005

To: William Cobern, Principal Investigator
Ozcan Gluacar, Student Investigator for dissertation

From: Mary Lagerwey, Ph.D., Chair Mary Lagerwey

Re: HSIRB Project Number: 05-11-27

This letter will serve as confirmation that your research project entitled "An Investigation of Successful and Unsuccessful College Chemistry Students' Stochiometric Problem-solving Performances" has been **approved** under the **expedited** category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may **only** conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: December 16, 2006

Walwood Hall, Kalamazoo, MI 49008-5456
PHONE: (269) 387-8293 FAX: (269) 387-8276

I. Project Description

I.1. Purpose

Many students view chemistry as one of the most difficult subjects (Stieff, 2002; Schmidt, 1997, Astudillo & Niaz, 1996). Learning chemistry places many demands on students and teachers that can seem overwhelming. Instructors often display mathematical formulas, chemical symbols and scientific measurements simultaneously to describe phenomena that are not visible to the student. Moreover, the "abstract" concepts of chemistry are often seen as confined to the chemistry classroom and not applicable outside of school. As a result, chemistry students have difficulty solving chemical problems such as stoichiometric problems.

Stoichiometry is one of the many complex topics in chemistry, which includes different problems involving combined material and equation balances, and mathematical calculations take a long time to solve. In order to be successful in these classes, learners need to have a series of skills, organized knowledge of chemistry, and knowledge of mathematics. Successful problem solving in stoichiometry involves calculating molecular weight of compounds, understanding and using of mole concept, writing equations, balancing them, knowing how to deal with ratios, doing mathematical calculations.

Although some students have enough knowledge of chemistry and mathematics and skills to solve simple problems, they surprisingly cannot use and link their knowledge pieces to do complex calculations. It seems that their knowledge is composed of isolated facts and separated through different domains. It is widely accepted that students' performance during problem solving is not only affected by students' knowledge structures (Bedard & Chi, 1992; Chi, Glaser, & Rees, 1982; Gerace, 2003) but also some other variables such as students' conceptual understanding of subject matter (Nakhleh & Mitchell,1993; Phelps, 1996; Nurrenbern & Pickering, 1987), proportional reasoning abilities (Dawkins, 2003; Lesh, Post, & Northern, 1988; Akatugba & Wallace, 1999; Kwon, Lawson, Chung, & Kim, 2000), cognitive developments (Atwater & Alick, 1990; Huitt & Hummel, 2003;Smith & Sims, 1992), and working memory capacities (Baddeley, 1986; Stamovlasis & Tsaparlis, 2000; Miller, 1956; Johnstone, 1983; Johnstone & Kellett, 1980).

In this study, I have two goals: (1) identifying, analyzing and better understanding of the differences between successful and unsuccessful

students' problem-solving performances, (2) investigating several variables simultaneously to better interpret students' behaviors, performances, and difficulties that students have while solving problems. However, I believe that these goals cannot be achieved easily without considering as many variables affecting stoichiometric problem solving as we can in our research. Therefore, in addition to being open minded as much as possible to explore the differences between successful and unsuccessful students' problem-solving activities, I am going to particularly consider and examine the influences of other variables, which are cited very often in the literature, on stoichiometric problem solving such as cognitive development, multiple intelligence, working memory capacity, proportional reasoning ability, conceptual understanding of particulate nature of matter and mole concept, and knowledge structure.

I.2. Research Questions

(1) Do the difficulties students have while solving stoichiometric problems stem from a poor understanding of prerequisite knowledge or do the difficulties stem from an inability to coherently link pieces of prerequisite knowledge into a cognitive structure necessary for successful problem solving?

(2) How are successful students' problem-solving performances different from those of unsuccessful ones?

(3) What are the roles of cognitive development, proportional reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in successful and unsuccessful students' problem-solving success in stoichiometry?

I.3. Research Design

Target Population

The target population consists of 14 college students enrolled in CHEM 116 at Purdue North Central University in spring 2006.

Data Collection

I am going to employ both qualitative and quantitative methods because I believe two methods may provide more richness and detail than one method to the study of problem-solving process. The quantitative data will be collected by administering different tests and scoring them. The qualitative data will be accumulated through the think-aloud protocols, problem-solving sessions. I will give detailed information for each test and think-aloud protocols respectively.

The first test subjects will take is the Test of Logical Thinking (TOLT) (Tobin & Capie, 1981; Tingle & Good, 1990). The TOLT (Appendix B) is a paper and pencil instrument which evaluates logical thinking. The first two items measure proportional reasoning, the third and fourth items measure the control of variables, the fifth and sixth items measure probabilistic reasoning, seventh and eight items measure correlational reasoning, and ninth and tenth items measure combinatorial reasoning. Each of the first eight items consists of two parts, an answer and a rationale for that answer. Both parts must be correct for the students to score on the item. On the items nine and ten the students must have every possible combination to score a point. The range on the test is from zero to ten. Students will be allowed 40 minutes to complete the TOLT.

This test has been used with students in several grades from middle school to college. The average score for eleventh grade chemistry students is around 4.5 out of ten. The reliability of this test ranges from .80 to .85. The TOLT has been shown to be a good predictor of chemistry achievement. However, the TOLT is not a direct measurement of chemistry achievement rather it is an indirect measurement of students' success in chemistry and especially in stoichiometry where the students really need to have good proportional reasoning ability. That's why, the proportional reasoning items have been found as the best predictors on the test (Gonzalez et al., 2005). Looking at the overall TOLT score, it appears that students scoring below 5 may have difficulty with chemistry, especially with quantitative aspects.

Second test in the study will be the Berlin Particle Concept Inventory (BPCI). The BPCI (Appendix C) was developed by Silke Milkelskis-Seifert in Germany and translated into English by a group of researchers at Kansas State University (Cui, Zollman, & Rebello, 2005). The BPCI contains 70 statements, each of which is rated on a four-point Likert Scale from true to false. Respondents also rate themselves as being either certain or uncertain of each answer. A reason for using the Likert Scale is that for most of the questions, the correct answer for a novice may be incorrect for an expert and even the experts may disagree based on their level of expertise. For example, it might be difficult to have consensus on the following statement: "Since particles exist, sooner or later their size and shape will be determined exactly." (Cui, Zollman, & Rebello, 2005). Moreover, Likert Scale questions allow us to study the vagueness of student choices that might better represent their mental models.

In the BPCI, the questions were categorized into eight categories because of vast coverage of the BPCI by Cui et al. (2005): (1) Existence of

particles and their experimental evidence, (2) relationship between characteristics of the individual particles and characteristics of the object they form, (3) material (air or vacuum) between the particles, (4) density, volume, mass, weight, and their relationship, (5) forces between particles, (6) difference between solid, liquid, and gaseous state, (7) relationship between shape, mass, and volume of the individual particles, (8) relationship between temperature and particle properties. The inter-rater reliability of the categories was 82% (Cui et al., 2005).

As third test, subjects will have the Longeot Test (LT) (Sheehan, 1970). The LT (Appendix E), originally published in French, is a paper-and-pencil test designed to measure various aspects of formal thinking. Its twenty – eight items are divided into four parts. The first part contains five items involving the concept of class inclusion. The second part of the test has six items of propositional logic while the third part consists of nine items designed to measure proportional reasoning. The fourth part of the test consists of eight combinatorial analysis problems requiring subjects to list all possible combinations of a set of items.

Validity and reliability of the English version of the Longeot test has been studied by earlier investigators (Pandey, Bhattacharya, & Rai, 1993; Sheehan, 1970; Ward et al., 1981). Sheehan's results (1970) indicated that the test was effective in differentiating between concrete and formal thinkers. Ward et al. (1981) found the test to be valid as scores exhibited a significant correlation ($r=.62$, $p<0.01$) with the sum of two Piagetian tasks (balance beam, flexible rods). They claimed the test to be reliable as the internal consistency ranged from 0.72 to 0.78 over a wide range of class type.

Fourth test in the study is the Mole Concept Achievement Test (MCAT)). This test (Appendix D) was developed by the researchers (Gower et al., 1977; Griffiths, Kass, & Cornish, 1983) to identify students' abilities in the following skills covering the mole concept and meaning of subscripts in chemical formulas (Yalcinalp, Geban, & Ozkan, 1995, p.1086):

> (1) Apply the definition of mole as it relates to the Avogadro's number of atoms or molecules and to the molar mass of an element or compound, (2) determine the number of atoms of a given kind or molecules... present in given mole quantities of elements or compounds, and vice versa, (3) convert a given mass of a compound or an element (or compound) to the number of moles represented, and vice versa, (4) convert the mass of a compound or an element.. to the number of molecules or atoms of the given type present, and vice versa, (5) determine the mass

> or the number of moles or the number of atoms of an element in a compound from a given mass or number of moles, or number of atoms of another element that is also present in the same compound.

Content validity of the test items was established by a group of experts in chemistry and science education. The reliability coefficient was estimated to be .88 (Yalcinalp, Geban, & Ozkan, 1995).

Fifth and the last test is the Digits Backwards Test (DBT) (Johnstone & El–Banna, 1986; Opdenacker et al., 1990). The DBT (Appendix F) consisted of reading to the subjects a set of digits and asking them to say them (or write them down) in reverse order. Thus 3245 would return as 5423. In the DBT, subjects will be asked to repeat a steadily increasing arbitrary sequence of digits in reverse order. The quantity of working memory capacity, X, is going to be defined as an integer corresponding to the maximum number of digits that can be repeated in reverse order without mistakes. Students participating in the test will repeat aloud and in reverse order the sequence of digits which is read by the researcher. The value of X will be taken to be the maximum number of digits, according to the minimum 50% correct criterion (Opdenacker et al., 1990).

Final piece of quantitative data is going to be collected by the results of think-aloud protocols. The stoichiometric and descriptive questions will be used during think-aloud protocols given in Appendix G and H. Subjects' problem-solving performances will be graded and regarded as the dependent variable in the study. The interaction between all variables and students' problem-solving achievements will be investigated statistically.

On the other hand, the only source of qualitative data, which is the main source of research data is think-aloud protocols. For the protocols, all subjects will be given several problems whose types were explained early in the design section. During these think-aloud protocols, problem-solving sessions, I am going to ask the subjects to think aloud and verbalize their thoughts as much as possible (Nakhleh, and Mitchell, 1993; Heyworth, 1999; Tingle & Good, 1990). I will also ask some probing questions similar to those that used in explicitation interviews. This is a special type of interview that attempts to discover as much as possible the spontaneous thinking of the subjects (Potvin, 2005). One of the most appropriate interview formats to elicit data concerning mental actions is the *explicitation* interview (Brodeur et al., 2005). This type of interview is based on specific techniques that lead the subject to a descriptive verbalisation of his or her lived past experience. It is through the analysis of the verbalizations describing these traces that the

interviewer can understand and acknowledge the existence of certain habits of thought.

One of the most important principles of this type of interview is that the interviewer must never ask questions that begin by the word "why" or questions looking for any type of justification. So the explicitation interview type is looking essentially for descriptions of "what is going on in the head" of the subject, according to the subject, when he explores the situations, instead of looking for justifications or ways to answer for his behavior. An example of frequently asked question during this type of interview would be: "When you said this (a prediction, for instance), what did you say to yourself at that moment?" (Potvin, 2005) We can then see that the main goal is to obtain *descriptions* instead of *constructions*. Thus, explicitation interview is also a tool that can free the subject from the need to satisfy the adult. As it is often said during these interviews, there are no right or wrong answers, just true ones.

While asking the questions during think-aloud protocols (explicitation interviews) - researcher needs to be extra careful not to ask the questions which make the interviewee explain what and why he has done. Rather, our goal is to understand what has happened in the interviewee (problem solver)'s mind just before he does something and to discover what are the things make problem solvers take some certain actions during the problem solving. I will record these talks on audiotapes and digital videotapes to be transcribed later for analysis (Heyworth, 1999). The camera will be set up in the interview room and pointed so as to only capture subjects' solutions on the papers, not the faces of the subjects.

Location

All the data will be collected at the Purdue North Central University. I will give the tests to the participants in SWRZ 239. The interviews with students will be conducted in SWRZ 234.

Duration

The study will occur between January 1, 2006 through January 1, 2007.

Study dissemination

The results of this study will be presented to the dissertation committee and other scholars in the field of science education. The findings

will be compared with related research, and might constitute a basis for publication or other presentations.

II. Data analysis

Throughout the data analysis, I will aim to answer my research questions: (1) Do the difficulties students have while solving stoichiometric problems stem from a poor understanding of prerequisite knowledge or do the difficulties stem from an inability to coherently link pieces of prerequisite knowledge into a cognitive structure necessary for successful problem solving? (2) How are successful students' problem-solving performances different from those of unsuccessful ones? (3) What are the roles of cognitive development, proportional reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in successful and unsuccessful students' problem-solving success in stoichiometry?

To be able to answer the first question, I will use mostly the qualitative data which will be collected throughout think-aloud protocols. First, I will code the transcripts using a software called Ethnoghraph, which is designed for analyzing and interpreting qualitative data. While coding the transcripts, I am going to look for the pieces particularly giving some information about subjects' knowledge structures and conceptual understanding. After completing coding process, I will start investigating all the data, test results, subjects' solution papers, and coded transcripts, I have. These codes can be seen in Appendix K. Although I will mainly focus on transcripts of problem-solving sessions, I will certainly triangulate the data collected by tests and the data collected by interviews- think-aloud protocols. I am planning to find out how successful subjects' knowledge structures are different from that of unsuccessful ones based on their explanations and solutions.

In order to answer the second research question, I will use both the qualitative data I gathered from problem-solving attempts and quantitative data collected as result of scoring of problems solved by subjects. Throughout the protocols, I will have chance to observe successful and unsuccessful subjects' problem- solving performances and have better idea about the differences, if exist, between both groups. I am going to also examine the quantitative data which I will obtain from the results of the problems solved about stoichiometry and gas laws. This piece of data also helps me understand better characteristics of both groups. Moreover, I'd like to see how successful chemistry students use their knowledge during problem solving, how they approach problem differently from the unsuccessful

students, and if the differences, cited in the literature, between successful (experts) and unsuccessful (novices) chemistry students really exist.

As for the third question, I analyze the data using statistical methods. First of all, to have broad idea about the individuals' skills, capabilities, and levels, descriptive statistics such as means, standard deviations, and the ranges of all variables will be calculated. Then Pearson correlation analysis will be run among five predictor variables, logical thinking (proportional reasoning ability), cognitive development, understanding of particle nature of matter and mole concept, working memory capacity. It is going to be investigated to see if the variables are correlated with each other and how. Finally, multiple regression analysis will be conducted for each of the subject to see how each variable influences the dependent variable, problem-solving performance.

III. Benefits of Research

I believe that the strength of this study, which leads to its significance, lies in its design. By yielding rich data about how students perceive and experience solving problems in stoichiometry, the study may constitute a great opportunity for the teaching evaluation, which further may inform the chemistry professors and the course designers in their effort to provide the best opportunity for learning chemistry and solving stoichiometry problems. I consider this fact extremely important - based on my teaching experience I know that for chemistry students this particular topic will be the one of the difficult topics in their chemistry education, therefore a unique opportunity to empower them. Their learning and perhaps most importantly, their lives may be improved if they leave the general chemistry courses with a better understanding of stoichiometry and necessary skills to solve the stoichiometry problems successfully.

By reflecting on how they learn chemistry and solve stoichiometry problems, participants may gain a better understanding of their own learning and problem-solving patterns. At a larger scale, this study may contribute to the discipline by adding to the knowledge of how to better teach chemistry to high school and college chemistry students.

IV. Subject Selection

Students' selection

I think the results of research using the same questions to analyze the problem-solving skills and performance of experts and novices will be controversial when experts are chosen among professors and novices are chosen among students. The questions used in the research might be true

problems to novices and simple exercises to experts. That's why, comparing the performance of experts, who are usually faculty or PhD students trained in the field, with that of novices, who are students enrolled in the course the first time, requires the design of problems difficult enough to require more than recall for the faculty and yet simple enough to allow the students a chance to obtain the solution (Smith & Good, 1984).

Although this can be done, it is also possible to find oneself comparing the performance of experts working on routine exercises with that of students working on novel problems. That's why it might be better if the successful students in the classroom are defined as experts and poor students are defined as novices (Heyworth, 1999) or simply successful students can be compared with unsuccessful ones in the same classroom (Camacho & Good, 1989).

For the reasons mentioned above I will choose my subjects from two different groups, successful chemistry students and unsuccessful chemistry students who are registered in general chemistry course, CHM 116, in spring 2006 (Heyworth, 1999). The chemistry course, CHM 116, is the continuation of CHM 115 which I run its labs during the fall 2005. Thus, I know the students from the previous semester. However, I am not involved in anyway with the teaching of CHM 116 in spring 2006 when the study will take place. I believe this will comfort students because they know they are going to work with someone they are familiar and the results of the study will not affect their grade in CHM 116.

After gaining HSIRB approval, with the consent of the faculty teaching the lecture, I (the student investigator), will inform students about the study, its purpose and design, and invite them to participate. In order to encourage interest in the research I will also highlight the possible contribution of the study to their and other students' learning of chemistry. I will make very clear the point that their participation in the study is completely voluntary and their decisions and actions will not have any negative impact on them. Assurance will be given to them that all the information provided will be strictly confidential.

In CHM 116, there are usually 52 registered students. I will not need all these students for problem-solving sessions. I will need less number of students to do in-depth interviews with them. Thus, I am going to use chemistry achievement test (CAT) and choose just 14 volunteer and eligible students grouped as successful and unsuccessful ones. I will determine successful and unsuccessful chemistry students based on their scores of CAT

including fifteen questions about stoichiometry, which can be seen in Appendix A.

CAT includes several questions evaluating the understanding of different variables involved in stoichiometric problem solving such as writing chemical formulas and reactions, balancing chemical equations, calculating molecular weight, finding excess and limiting reagent, and converting units into each other. All these variables together play an important role in determining someone's success in solving stoichiometry problems. 4 chemistry professors at two different universities have seen this test and they believe that this instrument is good enough to identify successful and unsuccessful students in stoichiometry.

Once volunteer students in CHM 116 read and sign the consent form after all their questions are answered, they will be ready to take CAT. I will grade all the tests and group them. Students score above 70% on the chemistry achievement test will be identified as successful and those who score below 40% on the same test will be identified as unsuccessful chemistry students. Among the students who score above 70%, I will choose 7 students and among those who score below 40%, I will again choose 7 students to continue my study with further tests and interviews.

Since I believe we can get more insight and information related to problem-solving performances using these two extreme groups, I will not be interested in those students who have average scores, between 40% and 70%. Although these are the percentages found as good numbers to identify successful and unsuccessful students by chemistry professors, there is a possibility that I can use different numbers based on the pattern of the all students' scores. The other reason why I am using these two groups is directly related to the one of the important goals of the research in education, finding methods and techniques to make students more successful. If we know where unsuccessful students have more difficulty and how and why successful students do good job while solving problems, we might be more helpful for poor students.

Later, I will contact the 14 subjects and let them know that they are found eligible for this study. I will also send thank-you message via e-mail to other volunteer students who take CAT and tell them I have chosen necessary number of students and they cannot participate in the study this time but they might be contacted in the future for different studies.

These subjects will be financially compensated for their time with a $12 payment at the end of each test-taking session and with a $7 payment at

the end of each interview. They will also receive an additional $8 bonus after the fourth interview if they attend all four interviews.

For the purpose of this research, fourteen students will be found. This number is consistent with the practice in other qualitative research found in the literature review. Considering the amount of time and effort necessary for conducting qualitative study and analysis of qualitative data, the number of subjects is going to be found reasonable and practical. I really do not worry about the gender of subjects because I am not interested in finding influence of gender on problem solving. In addition, literature does not show any significant findings related to the effect of gender on problem solving in chemistry.

V. Risk to Subjects

A potential inconvenience for students is that by its nature, a problem-solving session is time consuming, and they might find the process slightly tedious. Beside, they might find the questions and process difficult, which might cause some discomfort in the process of solving problems while thinking aloud. Nevertheless, there will not be any loss of class time except the time necessary for taking CAT whose result used to determine the subjects for this study. However, this time will be found at the end of the class time. This test will be given on a day that instructor dismisses the class early and the test will be completed in 30 minutes. During the test there will not be any other instructor, who might get involved in teaching CHM 116, in the room. The focus of this study is students' problem-solving performances, a topic generally considered non-sensitive, and I consider that the risk for participants is minimal. The best time for the problem-solving sessions will be decided together by investigator and subjects.

The subjects will not know there is any kind of classification or grouping among subjects. They all will be treated the same way. Thus, I don't worry about protecting unsuccessful students from social harm because nobody except me will know there is grouping among subjects such as successful and unsuccessful.

VI. Protection for Subjects

Participants will be informed ahead of time in regard to the design of the study and expectations, in terms of what exactly participants will do as part of the study. Assurance will be given to them that the focus of the study is exploration of differences among different problem-solving performances and that all information provided is strictly confidential. I will discuss the

design and expectations individually with the instructors in designated room, SWRZ 234, for problem-solving sessions.

During the study I will show interest and I will value all sorts of ideas coming from the participants, and I hope that in doing so, participants will feel not only comfortable sharing their views but also content that by their collaboration they can help chemistry educators in the effort to provide the best learning environment to the students.

The problem-solving sessions with the subjects will take place in room 234 in Schwarz Hall. This will assure that others will not know about the problem-solving sessions.

Participants are free not to answer any question(s) for whatever reason, or to quit at any time during the study. They can simply inform me that they are quitting the study or do not want to solve a problem.

The time inconvenience involving participants in the interview process will be addressed by allowing the participants to select the best time for the interview appropriate to their schedule.

VII. Confidentiality of Data

All the information collected from the participants is confidential. That means that their name or other identifying characteristics will not appear on any papers on which this information is recorded. The forms will be coded, and I will keep a separate master list with the names of participants and the corresponding code numbers. Once the data are collected and analyzed, the master list will be destroyed. All other forms will be retained in a locked file in the principal investigator's office for a minimum of three years.

VIII. Instrumentation

Oral recruitment scripts, interview scripts, instruments, think-aloud problems, and consent forms are attached in the Appendix.

IX. Informed Consent Process

All potential participants are college students. None of the potential pool of participants would be considered "at risk".

After gaining HSIRB approval, with the consent of the faculty teaching the CHEM 116, I will inform students about the study, its purpose and

design, and invite them to participate. If they are interested in learning more about the study I will show them the consent form and answer their questions. Once they decided to participate in this study, they will sign two copies of consent form. They will return one copy to me and keep the other one for themselves. Following signing consent forms, I will give them the CAT for identifying main subjects. Based on the results of this test, they might or might not be found eligible for the rest of the study. The 14 students will be eligible to be main subjects of the study. These students will be interviewed and will take more tests. Others will not do anything else. Main subjects, eligible 14 students, have the option to quit the study at any part of the data collection process without any penalty. They will receive all the payment to the point they completed. For example, if any of them decide to quit after the second interview, he or she will receive $24 dollars for test-taking sessions and $14 for the two interviews. Participation of subjects to the any part of the study is totally voluntary based. They can reject or decline taking any kind of test or instrument, or solving any question or they can quit the study at all any time.

Western Michigan University
Mallinson Institute for Science Education
Principal Investigator: Dr. William Cobern
Co-Investigator: Ozcan Gulacar

Consent form for student test-taking sessions and problem-solving sessions

I am invited to participate in a research project focused on finding details about college chemistry students' problem-solving performances. The purpose of the study is to explore how students' performances differ as they deal with more complicated stoichiometry problems and find out the causes behind the difficulties encountered during problem solving.

I will be asked to participate in no more than 4, 60 minutes think-aloud problem solving sessions, with Ozcan Gulacar at Schwarz Hall and no more than 2, 80 minutes test-taking sessions at Schwarz Hall. During the sessions I will be asked to provide general information about myself such as age, college status, background in math and science, and to describe my perceptions and experiences in regard to the learning of chemistry in general and stoichiometry in particular. I will also be asked to solve several stoichiometry problems with different difficulty levels while thinking aloud. I and student investigator (Ozcan Gulacar) will together decide the most proper times about when these sessions will take place.

A potential inconvenience for me is that by its nature, a problem-solving session is time consuming, and I might find the process slightly tedious. Beside, I might find the questions and process difficult, which might cause some discomfort in the process of solving problems while thinking aloud. Nevertheless, there will not be any loss of class time, and the think-aloud protocols will be conducted at a time that will be the most convenient to me, at a location that will assure that others will not know about the problem-solving sessions.

One way in which I may benefit from this activity is that by having the chance to reflect on how I learn chemistry and solve chemistry problems, I might gain a better understanding of my own learning and problem-solving patterns. In agreeing to participate in the study, others may benefit as well from the knowledge that is gained from this research. At a larger scale, this study may contribute to the discipline by adding to the knowledge of how to better study stoichiometry and solve problems about it.

I will be financially compensated for my time by a payment of $12 at the end of each test-taking session and a payment of $7 at the end of each interview. I

will also receive a bonus of additional $8 if I attend all four interviews. In other words, I will receive a payment of $15 at the end of the fourth interview if I have also participated in the first, second, and third interviews.

The results of this study will be presented to the dissertation committee and other scholars in the field of science education. The findings will be compared with related research, and might constitute a basis for publication or other presentations.

All the information collected from me is confidential. That means that my name or other identifying characteristics will not appear on any papers on which this information is recorded. The forms will be coded, and Ozcan Gulacar will keep a separate master list with the names of participants and the corresponding code numbers. Once the data are collected and analyzed, the master list will be destroyed. All other forms will be retained in a locked file in the principal investigator's office for a minimum of three years.

I am interested in participating in this study but I know that I first will take a test evaluating my problem solving in stoichiometry and my participation will be conditional upon taking the stoichiometry test; I might or might not be selected to participate.

I have the right to refuse to participate or quit at any time during the study without prejudice or penalty. If I have any questions or concerns about this study, I may contact Ozcan Gulacar at (219) 758-5494 or Dr. William Cobern at (269) 387-5407. I may also contact the Chair of Human Subjects Institutional Review Board at (269) 387-8298 or the Vice President for Research at (269) 387-8298 with any concerns that I have.

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board as indicated by the stamped date and signature of the board chair in the upper right corner. I should not sign this document if the corner does not have a stamped date and signature, or if the stamped date is older than one year. My signature below indicates that I have read and/or had explained to me the purpose and requirements of the study and I agree to participate.

_____ _____

Signature Date

Consent obtained by: _____ _____

Initials of researcher Date

Recruitment scripts for students

My name is Ozcan Gulacar and I want to conduct a study that has the purpose of exploring how students' performances differ as they deal with more complicated stoichiometry problems and find out the causes behind the difficulties. To get a deeper understanding in regard to "What is going on in problem solving" I want to triangulate the data from the test results, with data collected by interviews and document analysis.

To accomplish this goal I would like to invite you to participate in a series of think-aloud problem solving and test-taking sessions. The think-aloud problem solving sessions will be conducted in room 234 and test-taking sessions will be completed in room 239, Schwarz Hall, at a time that is the most convenient to you. The length of a problem-solving session is 60 minutes and the maximum number of these sessions is four. The length of test-taking session is 80 minutes and the maximum number of these sessions is two.

During the think-aloud problem solving sessions you will be asked to provide general information about yourself such as age, college status, background in math and science, and to describe your perceptions and experiences in regard to the learning of chemistry in general and stoichiometry in particular. In addition you will be asked to solve several stoichiometry problems with different difficulty levels while thinking aloud. All the information provided will be strictly confidential.

During the test-taking sessions you will take four tests measuring your understanding of different concepts and effects of different factors involved in stoichiometric problem solving such as proportional reasoning abilities and particular nature of matter. You will take these tests on two different days, two tests a day. All the data obtained will be strictly confidential.

If you are interested in learning more about this study but want to learn more, please contact me in person, by telephone (219-785-5494) or by email (ogulacar@pnc.edu) to set up a time to see the consent form and have your questions answered or I can contact you to answer your questions and give more information about this study until next class time If you write down your contact information, e-mail address or telephone number, on this paper (will be provided to students).

In the next class period, you will be asked to read and sign the consent form. After signing the consent form you will take a test measuring your understanding of stoichiometry. The results of this test help us to identify most appropriate subjects for this study. The results of this test will be strictly confidential. Your participation will be conditional upon signing the

consent form and taking the stoichiometry test, you might or you might not be selected to participate. Since this study involves in-depth interviews we can only have 14 students for this study. That's why; I need to do some kind of selection. The selection will not be merely based on how good or poor you do on this test, rather it will be based on a number of variables such as solutions showing important details about the students' conceptual understanding of several concepts involved in stoichiometry and the strategies used while solving problems. I will send a message to those, who will take the test but not selected as the main subjects for the study, to thank them for their great contribution and let them know that they can't participate in the rest of the study. I will also send e-mails to those who are selected as main subjects for the study and ask them for their proper times to come together and talk about the rest of the study.

Thank you very much!

Appendix B

Chemistry Achievement Test

(Since I do not have copyright of this test, I am unable to reprint it in the dissertation but it can be obtained from the http://www.sciencegeek.net/APchemistry/APtaters/chap03rev.htm)

Appendix C

The Test of Logical Thinking

(Since I do not have copyright of this test, I am unable to reprint it in the dissertation but it can be obtained from the http://www.as.wvu.edu/coll03/phys/www/rotter/phys201/1_Habits_of_the_Mind/Test_of_Logic_Thinking.html)

Appendix D

Berlin Particle Concept Inventory

(Since I do not have copyright of this test, I am unable to reprint it in the dissertation but those interested in getting a copy of the test can contact either Silke Mikelskis-Seifert (s.mikelskis@ipn.uni-kiel.de) for German version or Dean Zollman (dzollman@phys.ksu.edu) for English version.)

Appendix E

Mole Concept Achievement Test

(Since I do not have copyright of this test, I am unable to reprint it in the dissertation but those interested in getting a copy of the test can contact Serpil Yalcinalp (serpily@baskent.edu.tr).)

Appendix F

Longeot Test for Cognitive Development

(Since I do not have copyright of this test, I am unable to reprint it in the dissertation but those interested in getting a copy of the test can find it in the unpublished doctoral dissertation of Sheehan, D. at State University of New York, Albany (Please see bibliography for the full reference).)

Appendix G

Digits Backward Test for Working Memory Capacity

(The numbers for this test were generated by the author)

The list of the numbers for the digit backward test

1) Numbers with two digits
A.56 B. 98
C. 73 D. 41

2) Numbers with three digits
A.586 B.956
C.458 D.276

3) Numbers with four digits
A.8965 B.9674
C.6532 D.5834

4) Numbers with five digits
A.89654 B.45287
C.76354 D.96542

5) Numbers with six digits
A.653421 B.789354
C.692463 D.542893

6) Numbers with seven digits
A.4251368 B.5849632
C.3578642 D.4986318

7) Numbers with eight digits
A.75486382 B.69321548
C.96472512 D.36985417

8) Numbers with nine digits
A.964831721 B.864527314
C.352648971 D.246539875

9) Numbers with ten digits
A.4213697854 B.9864752312
C.5863219365 D.3452786491

10) Numbers with eleven digits
A.756843219874 B.216987453216
C.684239874519 D.145726895276

Appendix H

Stoichiometry Questions for Think-Aloud Protocols

The McGraw-Hill Companies

Mc Graw Hill **Education**

Contracts, Copyrights and Permissions

Two Penn Plaza
New York, NY 10121-2298
212 904 2574 Tel
212 904 6285 Fax

PERMISSION LICENSE: PRINT REPUBLICATION

Request ID/Invoice Number: OZC37525

Date: August 01, 2007

To: Ozcan Gulacar
3221 Dody Avenue, Apt. 3
Michigan City IN 46360
"Licensee"

McGraw-Hill Material

Author: Martin Silberberg
Title: CHEMISTRY: THE MOLECULAR NATURE OF MATTER AND CHANGE, 4/E © 2006
Description of material: 3 pages as outlined in your request of July 16, 2007 (ONLY)

Fee: $0

Licensee Work:

Author: Ozcan Gulacar
Title: An Investigation of Successful and Unsuccessful Students, Problem Solving [Doctoral Dissertation]
Publisher: Ozcan Gulacar
Publication Date: 2007
Distribution Territory: U.S.
Languages: English

Permission for the use described above is granted under the following conditions:

1. The permission fee of $0 must be received by The McGraw-Hill Companies on or before XXXX, and MUST BE ACCOMPANIED BY A SIGNED COPY OF THIS AGREEMENT. A check should be made payable to The McGraw-Hill Companies, and sent to The Permissions Department, The McGraw-Hill Companies, Two Penn Plaza, NY, NY 10121-2298. Please include the invoice number indicated at the top of this form on your check.

2. No adaptations, deletions, or changes will be made in the material without the prior written consent of The McGraw-Hill Companies.

3. This permission is non-exclusive, non-transferable, and limited to the use specified herein. The McGraw-Hill Companies expressly reserves all rights in this material.

4. A credit line must be printed on the first page on which the material appears. This credit must include the author, title, copyright date, and publisher, and indicate that the material is reproduced with permission of The McGraw-Hill Companies.

5. This permission does not allow the use of any material, including but not limited to photographs, charts, and other illustrations, which appears in a McGraw-Hill Companies' work copyrighted in or credited to the name of any person or entity other than The McGraw-Hill Companies. Should you desire permission to use such material, you must seek permission directly from the owner of that material, and if you use such material you agree to indemnify The McGraw-Hill Companies against any claim from the owners of that material.

Please sign both copies and return one to the McGraw-Hill Permissions Department, 2 Penn Plaza, 10th Floor, New York, NY 10121.

For McGraw-Hill

Ebony Rosa

Ebony Rosa
Permissions Department
McGraw-Hill Education

For Licensee:

Ozcan Gulacar

Name Ozcan Gulacar

Title Ph. D. Candidate

EXERCISES (SIMPLE STOICHIOMETRIC QUESTIONS)

1. WRITING AND BALANCING CHEMICAL EQUATIONS (4 QUESTIONS) *(Questions were taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.105)*

Write a balanced equation for each chemical statement:

E1) A characteristic of reaction of Group 1A elements: chunks of sodium react violently with water to form hydrogen gas and sodium hydroxide solution.

E2) The destruction of marble statuary by acid rain: aqueous nitric acid reacts with calcium carbonate to form carbon dioxide, water, and aqueous calcium nitrate.

E3) Halogen compounds exchanging bonding partners: phosphorus trifluoride is prepared by the reaction of phosphorous trichloride and hydrogen fluoride; hydrogen chloride is the other product. The reaction involves gases only.

E4) Explosive decomposition of dynamite: liquid nitroglycerin ($C_3H_5N_3O_9$) explodes to produce a mixture of gases- carbon dioxide, water vapor, nitrogen, and oxygen.

2. PERCENT COMPOSITION (1 QUESTION) *(Question was taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.93)*

E5) In mammals, lactose (milk sugar) is broken down to glucose ($C_6H_{12}O_6$), the key nutrient for generating chemical potential energy. What is the mass percent of each element in glucose?

3. DETERMINING EMPRICAL AND MOLECULAR FORMULAS (1 QUESTION) *(Question was taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.95&96)*

E6) Elemental analysis of a sample of ionic compound showed 2.82 g of Na, 4,35g of Cl, and 7.83g of O. What is the empirical formula and name of the compound?

E7) During physical activity, lactic acid (M=90.08 g/mol) forms in muscle tissue and is responsible for muscle soreness. Elemental analysis shows that

this compound contains 40.0% C, 6.71% H, and 53.3% O by mass. Determine the molecular formula of lactic acid.

4. PERCENT YIELD (1 QUESTION)
(Question was taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.114)

E8) Silicon carbide (SiC) is an important ceramic material that is made by allowing sand (silicon dioxide, SiO_2) to react with powdered carbon at high temperature. Carbon monoxide is also formed. When 100.0kg of sand is processed, 51.4kg of SiC is recovered. What is the percent yield of SiC from this process?

5. LIMITING REAGENT (1 QUESTION)
(Question was taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.113)

E9) A fuel mixture used in early days of rocketry is composed of two liquids. Hydrazine (N_2H_4) and dinitrogen tetraoxide (N_2O_4), which ignite on contact to form nitrogen gas and water vapor. How many grams of nitrogen gas form when 100g of N_2H_4 and 200g of N_2O_4 are mixed?

6. MOLE CONCEPT (3 QUESTIONS)
(Questions were taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.91)

E10) Silver (Ag) is used in jewelry and tableware but no longer in U.S. coins. How many grams of Ag are in 0.0342mol of Ag (M=107.9 g/mol)?

E11) Iron (Fe), the main component of steel, is the most important metal in industrial society. How many Fe (55.85 g/mol) atoms are in 95.8 grams?

E12) Graphite (M= 12.01 g/mol) is the crystalline form of carbon used in "lead" pencils. How many moles of carbon are in 315mg of graphite?

7. CONVERTING UNITS AND RATIOS

A. IN CHEMICAL CONTEXT (2 QUESTIONS)
(Questions were taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.107)

E13) In a lifetime, the average American uses 1750lb (794kg) of copper in coins, plumbing and wiring. Copper is obtained from sulfide ores, such s

chalcocite, or copper (I) sulfide, by a multistep process. After an initial grinding, the first step is to "roast" the ore (heat it strongly with oxygen gas) to form powdered copper (I) oxide and gaseous sulfur dioxide.

A) How many moles of oxygen are required to roast 10.0 mol of copper (I) sulfide?

B) How many grams of sulfur dioxide (M=64.07 g/mol) are formed when 10.0 mol of copper (I) sulfide is roasted?

B. IN MATHEMATICAL CONTEXT (2 QUESTIONS)
(Questions were taken from the textbook called Chemistry –The molecular nature of matter and change by Silberberg, 2006, p.15)

E14) A furniture factory needs 31.5ft^2 of fabric to upholster one chair. Its Dutch supplier sends the fabric in bolts of exactly 200m^2. What is the maximum number of chairs that can be upholstered by 3 bolts of fabric? (1 m=3.281 ft)

E15) To wire your stereo equipment, you need 325 centimeters of speaker wire that sells for $0.50/ft. What is the price of the wire?

PROBLEMS (COMPLEX STOICHIOMETRIC QUESTIONS)

P1. (Silberberg, p.130, 2006, q#3.109)
Narceine is a narcotic in opium. It crystallizes from water solution as hydrate that contains 10.8% H_2O by mass. If the molar mass of Narceine hydrate is 499.52 g/mol, determine x in narceine.xH_2O.

P2. (Silberberg, p.131, 2006, q#3.116)
During the studies of the reaction in the reaction

$$N_2O_4\ (l) + 2N_2H_4\ (l) \rightarrow 3N_2\ (g) + 4\ H_2O\ (g)$$

A chemical engineer measured a less-than-expected yield of N2 and discovered that the following side reaction occurs:

$$N_2O_4\ (l) + 2N_2H_4\ (l) \rightarrow 6NO\ (g) + 2\ H_2O\ (g)$$

In one experiment, 10.0 g of NO formed when 100.0 g of each reactant was used. What is the highest percent yield of N_2 that can be expected?

P3. (Silberberg, p.130, 2006, q#3.113)
Isobutylene is a hydrocarbon used in the manufacture of synthetic rubber. When 0.847g of isobutylene was analyzed by combustion, the gain in mass of the CO_2 absorber was 2.657 g and that of the H_2O absorber was 1.089g. What is the empirical formula of isobutylene?

P4. (Silberberg, p.132, 2006, q#3.132)
Hydrocarbon mixtures are used as fuels. How many grams of CO_2 (g) are produced by the combustion of 200 g of a mixture that is 25% CH_4 and 75% C_3H_8 by mass?

P5. (Silberberg, 2006, p.132, q#3.135)
A 0.652-g sample of a pure strontium halide reacts with excess sulfuric acid, and the solid strontium sulfate formed is separated, dried, and found to weigh 0.775g. What is the formula of the original halide?

P6. (Silberberg, 2006, p.132, q#3.136)
Methane and ethane are the two simplest hydrocarbons. What is the mass % of C in a mixture that is 40% methane and 60% ethane by mass?

P7. A 1.2048g sample of Na_2CO_3 is dissolved and allowed to react with a solution of $CaCl_2$. The resulting $CaCO_3$, after precipitation, filtration, and drying, was found to weigh 1.0362g. Calculate the percent yield of the $CaCO_3$.
($CaCO_3$: 100 g/mol; Na_2CO_3: 106 g/mol; $CaCl_2$: 111 g/mol; NaCl: 58.5 g/mol)
(Hint: The unbalanced reaction is $Na_2CO_3 + CaCl_2 \rightarrow CaCO_3 + NaCl$)

P8. *(Since I do not have copyright of the question, I am unable to print it in the dissertation but those interested in getting a copy of the question can find it in the following link)*
http://www.andrew.cmu.edu/course/09-105/GIF97_1/F05.MIwo.3.gif

P9. *(Since I do not have copyright of the question, I am unable to print it in the dissertation but those interested in getting a copy of the question can find it in the following link)*
http://www.andrew.cmu.edu/course/09-105/GIF97_1/F05.MIIwo.3.gif

P10. *(Since I do not have copyright of the question, I am unable to print it in the dissertation but those interested in getting a copy of the question can find it in the following source)*

(Goldberg, D.E., chemistry 3000 solved problems in, McGraw Hill, 1987, p.172, q#11.43)

P11. (Chang, 2007, p.114, q#3.127) A compound made up of C, H, and Cl contains 55 percent Cl by mass. If 9.00 g of the compound contain 4.19×10^{23} H atoms, what is the empirical formula of the compound?

P12. The decomposition reaction of calcium carbonate is represented by the following balanced equation:

$$CaCO_3\ (s) \rightarrow CaO\ (s) + CO_2\ (g)$$

After 13.2-g sample of calcium carbonate was heated in an open container to cause decomposition, the mass of the remaining solid was determined to be 7.74g. The student is unsure if the reaction is complete, so the solid could contain unreacted $CaCO_3$.
(CaO: 56 g/mol; $CaCO_3$: 100 g/mol; CO_2: 44 g/mol)

a) Can you prove whether or not the reaction is complete?
b) What would be the actual mass of CaO if both CaO and CO_2 have the same percent yield?

Appendix I

Further Differences between Successful and Unsuccessful Students

(To be operationalized in a future study)

Investigating the Problem Solving Habits

After checking the types of the errors and their frequencies in the students' solutions, we wanted to check the other variables, which were not necessarily wrong but maybe ineffective and inefficient and affecting the students' successes in solving the problems. We knew that these variables such as the first and the last thing done while solving problems did not directly affect the students' answers but indirectly influenced the students' performances in a negative or positive way depending on what was done. These variables can also be called as problem solving habits.

Perspective When Starting Problems (Conceptual vs. Algorithmic)

In this part, we investigated students' first steps and tried to find out their preferences as first step. We were wondering if the students were trying to understand what the question was really asking or focusing on other details such as equations and numbers and writing down the equations as the first step. In our study, we found that both successful and unsuccessful students appeared to prefer writing the formulas or equations down as the first step rather than trying to understand the question before doing any calculation, which was seen as a more efficient and conceptual way to start the solution of the problems.

While investigating the students' first step and making inferences, we were aware that we cannot claim that the students who wrote the equations as first step did not think what the question was asking first since we cannot read the problem solvers' minds. We made inferences solely based on students' behaviors and sayings during the first step as well as examinations of what they did after the first step. Before we discuss about our findings about their second steps and its relation to our inference related to their first step, we want to talk about the statistical significance of the findings in terms of illuminating the differences between successful and unsuccessful students.

The calculated significant levels for what was done as the first step revealed that there was not a significant difference between the successful and unsuccessful students in terms of their preference in the first step. This finding was surprising for us because we were assuming to see that successful students would prefer more conceptual way to start the questions and try to understand the question first but it did not happen. They like unsuccessful students preferred to write down the equations and formulas down as first step. We could not make sense of this and as we decided before we did further analysis and examined how students were doing after the first step whether they were fluent or hesitant about what to do.

Table 4.26
The Differences in Perspectives on Starting Problems and Fluency of Work
(*Significant difference at the 0.05 level)

SBJ	CAT	First Thing They Do				Hesitation or Fluency			
		Writing Down		Trying to Understand		Hesitation		Fluency	
p values		*.39*		*.39*		*.01**		*.01**	
01	S	12	**103 (55%)**	9	**86 (45%)**	15	**119 (63%)**	6	**70 (37%)**
03	S	13		8		14		7	
07	S	8		13		17		4	
09	S	13		8		13		8	
10	S	15		6		9		12	
11	S	13		8		10		11	
14	S	9		12		9		12	
15	S	8		13		19		2	
18	S	12		9		13		8	
02	U	8	**84 (50%)**	13	**84 (50%)**	16	**136 (81%)**	5	**32 (19%)**
04	U	9		12		17		4	
06	U	13		8		15		6	
08	U	9		12		18		3	
12	U	10		11		16		5	
13	U	11		10		18		3	
16	U	13		8		19		2	
17	U	11		10		17		4	

We were thinking that if a student did write an equation as a first step and continued his solution without hesitation, we would interpret that student's first step was efficient because the student knew the solution and did thinking quickly and implicitly. On the other hand, if a student wrote an equation or formula as his first step and showed a hesitation, we would interpret that student's first step was ineffective because the student did not

really know how to solve the problem and did not think about the question and plan his solution.

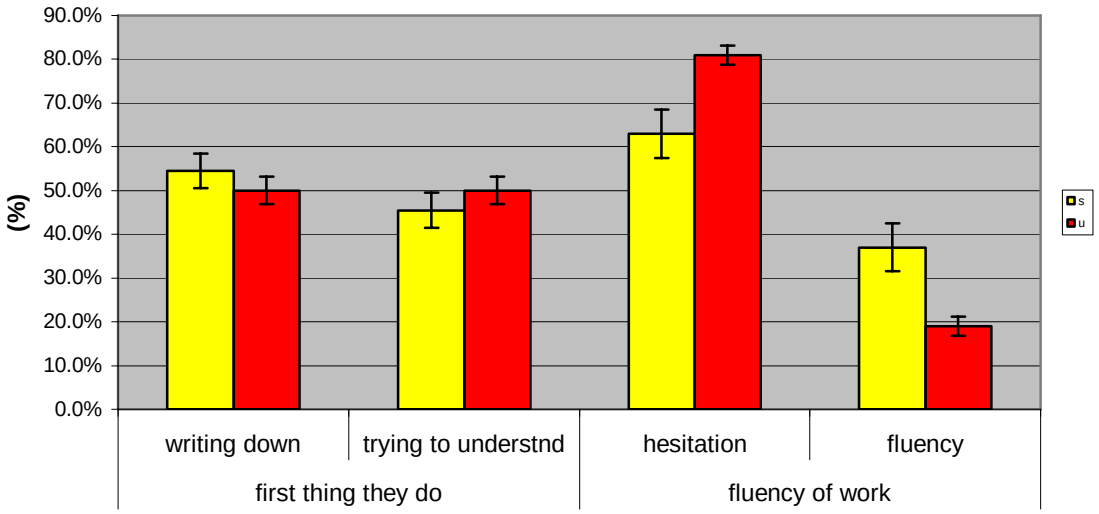


Figure 4.12: The Differences in Perspectives on Starting Problems and Fluency of Work

We think before we discuss the findings about the fluency and hesitation in detail, we need to describe what we meant by hesitation and fluency. If the student pauses for a while and does nothing or goes back to question and reads the question, we interpreted that student has hesitation about what to do next. Here it is difficult to talk quantitatively about the pausing time, it is based on our observation and interpretation of students behaviors. If the student does not pause and goes to next step fluently, we interpreted that students is fluent.

Fluency of Work (Fluency vs. Hesitation)

The investigation of the fluency of work after the first step showed that there is a significant difference between the unsuccessful and successful students' fluencies at their solutions. The successful students were significantly more fluent at their solutions than unsuccessful students were. This was a sign for us to believe that unsuccessful students were writing down the equations first because they were using an ineffective strategy to start their solutions. On the other hand, the successful students did write the equations and formulas because they automatically recognized the type of the questions and decided what to do in their minds without talking aloud and making it explicit. Therefore, writing the equations as a first step for them was not perceived as an inefficient strategy.

This new finding reminded us Bodner's (1987) definition of problem solving, which stressed on the subtle interaction between the task and the individual solving it. We believed that some of the problems were not the true problems for all of our students but simple exercises whose solutions were known by solver at the beginning. It made sense because we know that especially experts do not think about the solutions rather they start solving the question by putting the equations down and solve the question without any difficulty and hesitation when they do exercises.

Perspective of Overall Approach (Conceptual vs. Algorithmic) and Methods (Working Forward vs. Means-End)

In the following part, we investigated the students' preferences in using the methods and reasons behind those methods in order to interpret the students' problem solving performances and understand the problem solving process better. We also investigated the students' approach to the problems and their goals in the problems.

There seem to be two common approaches and two methods preferred by most students. We defined the students' approaches based on our observations of students' behaviors and interpretations of students' transcripts and called them as conceptual and algorithmic thinking. We interpreted students' approach as algorithmic thinking when they solve the problems to get a unit or a number. They explicitly say that we want to or we need to get this unit or implicitly mean it. Moreover, we used the analysis of their transcripts to identify what their approaches really were. Transcripts also revealed that they were solving the question unconnectedly from the related concepts simply to get an answer, not necessarily the right one. On the contrary, students who we classified as conceptual thinkers were solving the problems in a way that was more conscious of the conceptual context. They seemed to know what they were looking for and saw its relation with the concepts and its place in the big picture. They were not solving the

problems simply to get a number or a unit unconnected from the concepts but to get the answer, which would conceptually make sense to them.

After defining the algorithmic and conceptual thinking or approaches, we examined each question and classified students' approach as conceptual and algorithmic as well as added them to find the totals for each student as represented in the Table 4.27.

In the same manner, we defined two common methods employed by students. The first common method as mostly cited in the literature and attributed to experts was working-forward method. We identified students' strategy as working forward method when they at the beginning knew what the question was about and had a method to solve the problem. It looked that students were solving an exercise. The solution was straightforward. On the other hand, we identified students' method as means-ends analysis when they did not know how to go from where they were to where the wanted to be. Moreover, they were focusing on unknowns and usually ignoring the realities of the situation described in the question. They were trying to apply the different strategies, which worked before for them, to get an answer.

Here, we should make clear that there were different degrees of each method although we could not quantify them. There were some students who used purely means-ends analysis with no clear goal and there were some students who partially knew what they would get at the end but did not know

exactly how to cross that gap therefore they tried multiple methods until they find the right strategy.

Table 4.27
The Comparison of Thinking Styles of Successful Subjects to those of Unsuccessful Ones (*Significant difference at the 0.05 level)

SBJ	CAT	Overall Approach		Methods	
		Conceptual Thinking (CT)	Algorithmic Thinking (AT)	Working Forward (WF)	Means-Ends Analysis (ME)
p values		***.02****	***.00****	***0.06***	***.00****
1	S	22	4	24	5
3	S	21	4	22	10
7	S	21	3	25	3
9	S	20	4	24	6
10	S	22	2	23	3
11	S	22	0	25	2
14	S	22	1	25	2
15	S	21	5	24	5
18	S	21	1	25	2
T		**192.0 (89%)**	**24.0 (11%)**	**217.0 (85%)**	**38 (15%)**
2	U	21	5	22	10
4	U	18	9	20	14
6	U	20	9	23	8
8	U	20	9	22	9
12	U	20	3	25	3
13	U	17	10	23	8
16	U	6	17	8	18
17	U	13	12	20	10
T		**135.0 (65%)**	**74.0 (35%)**	**163.0 (67%)**	**80 (33%)**

Again, we followed a similar way as we followed in finding students' approaches in each question; we checked each question and identified students method based on our definitions. One more thing reader should keep in mind that since the number of questions completed (solved) by the

students varies, the total number of conceptual and algorithmic approaches as well as the total number of working forward and means-ends analysis methods show variety for students.

While analyzing the students' methods and approaches to the questions, we found out that there is a strong relationship between the methods used by the students and their perspective about their fundamental mission and task in solving the problems. When we examined the Table 4.27 and Figure 4.13, we saw that the interaction between the thinking styles and methods better. The percents of the thinking styles for both successful and unsuccessful students appeared to be very close to the percents of the methods followed by both successful students and unsuccessful students.

Although while solving the problems successful students sometimes saw their task as getting a number or finding an answer with the unit they thought as the right one, unsuccessful students appeared to be more algorithmic thinkers, which meant they were more likely to approach the problems algorithmically. The t-test results also supported this finding and revealed that successful students approach the problems conceptually significantly more than unsuccessful students do. In parallel with students' overall approach on problem solving, students tended to use the means-ends analysis when they solved the problems for a unit or a number and did not really know what they needed to do. On the other hand, students preferred to

use the working forward method when they solved the problems conceptually and knew what they need to do.

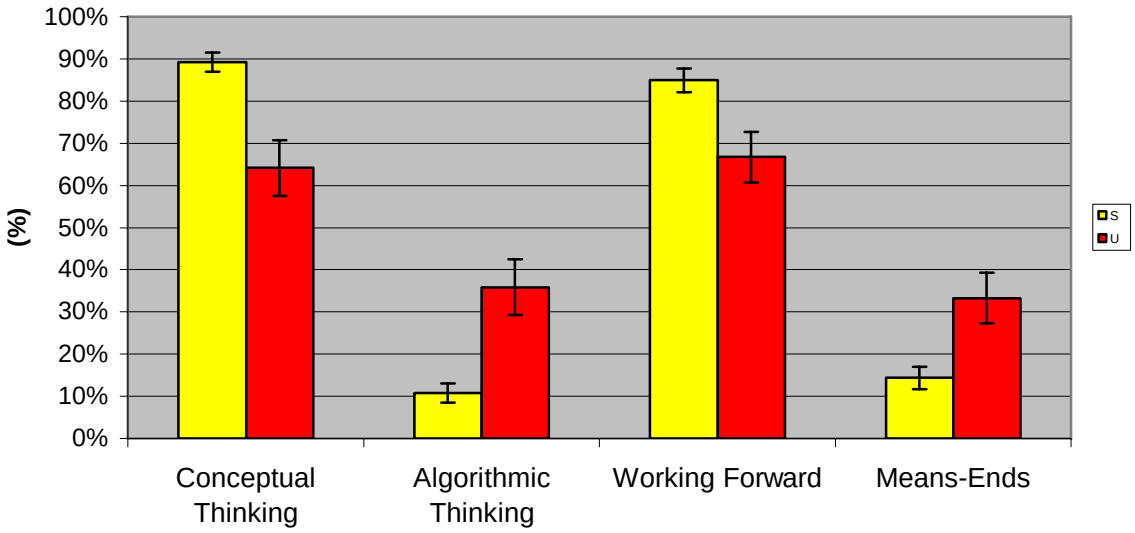


Figure 4.13: Comparison of Students' Overall Approach and Methods

These results make better sense when we consider the meanings of the conceptual and algorithmic approaches along with the functions of the working forward and means-ends analysis. If a student was approaching a problem algorithmically, it meant that the student did not know where the solution was going and was solving the problem just for the sake of finding a number or a unit. The student who approached a problem conceptually, however, knew what he was doing and saw the relationship between his calculations and the big picture. Therefore, this type of students preferred the working forward method because the general use of the working forward method was the best fit for their approach. This method was used when the solution of the question was more or less known by the students. It did not

mean that the students knew the whole solution at the beginning, but they knew what to expect from the solution of the problem. Thus, the students, in this method, looked at the givens in the problem and then moved from the statement of the problem to a physical representation of it and finally to an answer.

On the other hand, means-ends analysis was the best fit for the other groups of the students who were approaching the problems algorithmically because this method was used especially when the students did not know what to do. However, the closer analysis of the students' use of the means-ends analysis revealed that this method was used by the students in two different cases. The first one was that when they had no clue what to do to solve the problem and where the solution was going. They generated different formulas, did unnecessary calculations, or transferred the strategies from the other questions without knowing if that was the right strategy for them for that question. In the second case, students had some ideas about the solution and they knew more or less what to expect at the end of the solution but they were not sure which strategy would work best for them. Then, they used different strategies in turn until getting an answer, which they thought made sense.

At the end, we checked the t-test results to see if there is a significant between the use of the methods by successful and unsuccessful students. The results, surprisingly, did not show significant difference between the use of

working forward method but the use of means-ends analysis between successful and unsuccessful students. It was surprising for us because we expected to see the results the other way, significant difference for the use of working forward method not for the means-ends analysis. We were thinking that way because we knew that that successful students use the working forward method significantly more than unsuccessful students since they were more successful and straightforward in their solutions. Moreover, we knew that both unsuccessful and successful students usually preferred means-ends analysis when they did not know what to do. Therefore, we thought it should not have showed a significant difference.

Checking Final Answer (Checking vs. not Checking)

Like we determined the differences in students' actions at the first step, overall approaches, and methods followed, we observed differences in students' choices at the last step of their solutions as well. Successful students appeared to be significantly more conceptual checkers than the unsuccessful students are. Here, we need to make a point clear. The results could not be interpreted as the same students always checked their answers conceptually and again the same students always checked their answers mathematically. This is not the case. As we see in Table 4.28, every student, regardless of the group he was involved, checked the answers sometimes conceptually and sometimes mathematically.

Table 4.28
Students' habit of checking the answers
(*Significant difference at the 0.05 level)

SBJ	CAT	Last Thing They Do					
		Checked Conceptually		Checked Math		Did not Check	
p values		***.00****		***0.09***		***.00****	
1	S	3	26.0 (11%)	6	50.0 (21%)	17	158.0 (68%)
3	S	4		6		16	
7	S	2		4		20	
9	S	3		6		17	
10	S	4		4		18	
11	S	3		4		19	
14	S	4		8		14	
15	S	1		5		20	
18	S	2		7		17	
2	U	1	7.0 (3%)	5	35.0 (17%)	20	166.0 (80%)
4	U	1		4		21	
6	U	1		6		19	
8	U	1		4		21	
12	U	2		5		19	
13	U	1		2		23	
16	U	0		4		22	
17	U	0		5		21	

It is an important sign to believe that students' strategies are affected by the context of the questions. If the students had a good understanding of the concepts involved in the questions and were familiar with the context of the question as we clearly observed in mathematical-ratio questions, they easily check their answers. On the other hand, if the students had a poor conceptual knowledge, they either preferred not to check the answers at all or checked the answers in terms of their algorithm.

It was clear that unsuccessful students were different from the successful ones in terms of their preference of checking the answers. Especially, when the issue came to the checking the solution as a whole as the students progressed in their solutions, the difference in the students' preference of checking the solutions got clearer.

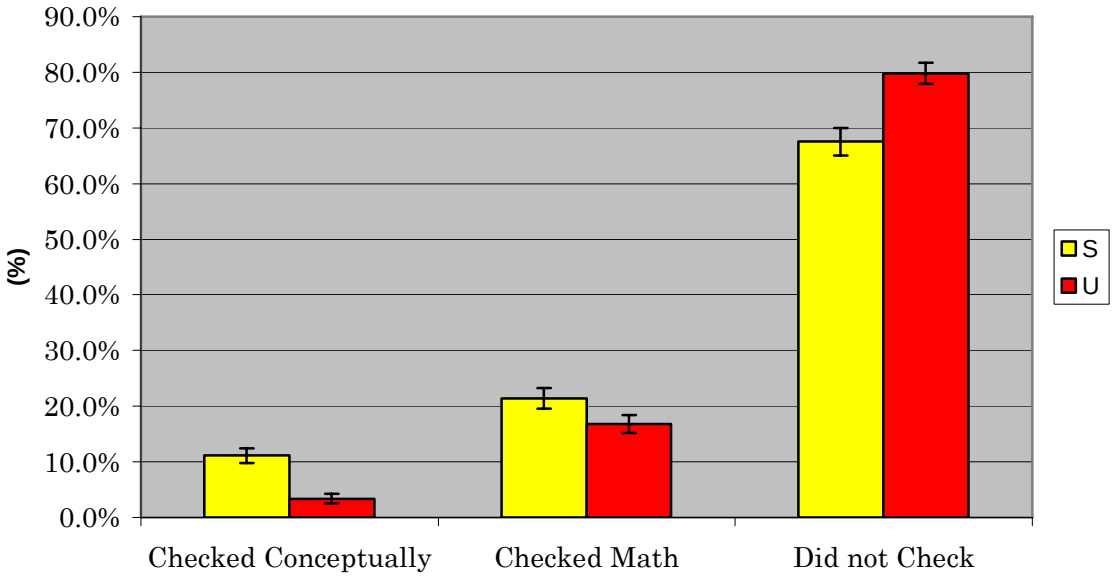


Figure 4.14: Students' Habit of Checking Answers

The successful students tended to check their solutions more as a whole than the unsuccessful students did. They were more successful at determining the little mistakes easily, and getting the right answers since they were competitive with the context and pieces of the question. However, unsuccessful students could not check their solutions as they were working on their solutions since they were not familiar with the types of the questions and the complexity of the questions used students' all working memory

capacities, which prevented students' thinking about the details and detection of the errors in their solutions. Although we were aware that successful students did not check their solutions as a whole all the time, they did more checking than unsuccessful students did.

BIBLIOGRAPHY

Akatugba, A.H. & Wallace, J. (1999). Sociocultural influences on physics students' use of proportional reasoning in a non-western country. *Journal of Research in Science Teaching*, *36*(3), 305-320.

AAAS (2001). *Atlas of science literacy*. Washington: American Association for the Advancement of Science.

Anderson, J.R. (1993). *Rules of the mind*. Hillsdale, NJ: Lawrence Erlbaum.

Ashmore, A.D., Frazer, M.J., & Casey, R. J. (1979). Problem solving and problem solving networks in chemistry. *Journal of Chemical Education, 56*(6), 377-379.

Asieba, F.O., & Egbugara, O.U. (1993). Evaluation of secondary pupil's chemical problem-solving skills using a problem-solving model. *Journal of Chemical Education*, *70*(1), 38-39.

Astudillo, L.R., & Niaz, M. (1996). Reasoning strategies used by students to solve stoichiometry problems and its relationship to alternative conceptions, prior knowledge, and cognitive variables. *Journal of Science Education and Technology, 5*(2), 131-140.

Ault, A. (2001). How to say how much: Amounts and stoichiometry. *Journal of Chemical Education, 78*(10), 1347-1349.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York, NY: Holt, Rinehart and Winston, Inc.

Atwater, M. M., & Alick, B. (1990). Cognitive development and problem solving of Afro-American students in chemistry. *Journal of Research in Science Teaching, 27*(2), 157-172.

Ayas, A., & Demirbas, A. (1997). Turkish secondary students conceptions of introductory chemistry concepts. *Journal of Chemical Education*, *74*(5), 518-521.

Baddeley, A. (1976). *The psychology of memory*. New York, NY: Basic Books.

Baddeley, A. (1986). *Working memory*. Oxford, UK: Clarendon Press.

Baddeley, A. (1999). *Essentials of human memory.* Hove, England : Psychology Press.

Bargellini, A., (2005). Some experiences of innovation in experimental sciences teaching, at compulsory school level, in Italy. Retrieved on February 23, 2005 from http://www.pa-inz.ac.at/international/Didaktik /extern /ModulesProgress/bargelli.htm

Bauer, R.C., Birk, J.P., & Marks, P.S. (2007). *A conceptual introduction to chemistry*. New York, NY: McGraw-Hill Companies.

Bedard, J. and Chi, M. T. H. (1993). Expertise. *Current Directions in Psychological* Science, *1* (4), 135-139.

Bell-Loncella, E.T. (2003). A few words about solving problems in chemistry. Retrieved on March 12, 2004, from http://users.kfupm.edu.sa/CHEM /zseddigi/a_few_words_about_solving_proble.htm.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986) Is an atom of copper malleable? *Journal of Chemical Education*, *63*(1), 64-66.

Bodner, G. M. (1987). The role of algorithm in teaching problem solving. *Journal of Chemistry Education*, *64*(6), 513-514.

Bodner, G. M. (1991). Toward a unified theory of problem solving: A view from chemistry. In Smith, M.U. (Ed) *Toward a unified theory of problem solving*, (pp.21-34). Hillsdale, NJ: Lawrence Erlbaum Associates.

Bodner, G.M., & Domin, D.S. (1995). The Role of representations in problem solving in chemistry. *Toward a cognitive-science perspective for scientific problem solving: A Monograph of the National Association for Research in Science Teaching, 6*, 245-263.

Bodner, M.G., & Domin, S.D. (2000). Mental models: The role of representations in problem solving in chemistry. *University of Chemistry Education*, *4*(1), 24-30.

Bodner, G. M., & Herron, J. D. (2002). Problem solving in chemistry. In J.K.Gilbert et al., (Eds.), *Chemical education: Towards research-based practice*, (pp. 235-266). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Bodner, G.M. (2003). Problem Solving: The difference between what we do and what we tell students to do. *University of Chemistry Education, 7*, 37-45.

BouJaoude, S., Salloum, S., & Khalick, F.A. (2004). Relationship between selective cognitive variables and students' ability to solve chemistry problems. *International Journal of Science Education, 26*(1), 63-84.

BouJaoude, S., & Barakat, H. (2003). Students' problem-solving strategies in stoichiometry and their relationship to conceptual understanding and learning approaches. *Electronic Journal of Science Education, 7*(3). Retrieved on April 15, 2007 from http://wolfweb.unr.edu/homepage/ crowther/ejse/boujaoude.pdf

BouJaoude, S., & Barakat, H. (2000). Secondary school students' difficulties with stoichiometry. *School Science Review, 81*(296), 91-98.

Bransford, J. (1979). *Human cognition: Learning, understanding, and remembering*. Belmont, CA: Wadsworth

Bransford J.D., Brown, A. L., & Cocking R. R. (Eds.). (2002). How experts differ from novices. *How people learn*, (pp.31-51). Washington, DC: National Academy Press.

Breslow, L. (2001). Transforming novice problem solvers into experts. *Transforming Novice Problem Solvers into Experts*, *13*(3). Retrieved on February 28, 2005 from http://www.mit.edu/afs/athena/org /t/tll/published/transforming_novice.htm.

Brodeur, M., Deaudelin, C., Mercier, J., & Legault, F. (2005). Measuring self-regulated learning in a teaching practicum context. Retrieved on May 10, 2005 from http://crll.gcal.ac.uk/conf/Abstracts/05-155.doc.

Bunce, D. M., & Heikkinen H. (1986). The effects of an explicit problem solving approach on mathematical chemistry achievement. *Journal of Research in Science Education, 23*(1), 11-20.

Bunce, D. M. Gabel, D., and Samuel, J. (1991). Enhancing chemistry problem solving achievement using problem categorization. *Journal of Research in Science Teaching, 28*(6), 505-521.

Bunce, D.M. & Gabel, D. (2002). Differential effects on the achievement of males and females of teaching the particulate nature of chemistry. *Journal of Research in Science Teaching, 39*(10), 911-927.

Cantu, L.L., & Herron, J.D. (1978). Concrete and formal Piagetian stages and science concept attainment. *Journal of Research in Science Teaching, 15*(2), 135-143.

Caramazza, A., McCloskey, M., & Green, B. (1981). Naïve beliefs in "sophisticated" subjects: Misconceptions about the trajectories of objects. *Cognition*, *9*(2), 117-123.

Caracelli, V.J., and Greene, J.C. (1997). Crafting mixed-method evaluation design. In J. C. Greene and V. J. Caracelli (eds.), *Advances in mixed-method evaluation: The challenges and benefits of integrating diverse paradigms.* New Directions for Program Evaluation, No. 74, (pp. 19-32). San Francisco, CA: Jossey-Bass.

Camacho, M., & Good, R. (1989). Problem solving and chemical equilibrium: Successful versus unsuccessful performance. *Journal of Research in Science Teaching*, *26*(3), 251-272.

Chandran, S., Treagust, D.F., & Tobin, K. (1987). The role of cognitive factors in chemistry achievement. *Journal of Research in Science Teaching*, *24*(2), 145-160.

Chang, R. (2007). *Chemistry. 9th edition.* New York, NY: McGraw-Hill Companies.

Chi, M. H. T., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121–152.

Chi, M. T. H., Glaser, R. & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence,*, (pp. 7-76). Hillsdale, NJ: Erlbaum.

Chi, M. T. H., Slotta, J.D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. Learning and instruction - The *Journal of the European Association for Research on Learning and Instruction*, *4*(1), 27-43.

Chiu, M. H. (2001). Algorithmic problem solving and conceptual understanding of chemistry by students at a local high school in Taiwan. *Proceedings of National Science Council, 11*(1), 20-38. Retrieved on February 28, 2005, from http://nr.stic.gov.tw/ejournal/ProceedingD/v11n1/20-38.pdf

Chiu, M. H., Chou, C.C., & Liu C.J. (2002). Dynamic processes of conceptual change: analysis of constructing mental models of chemical equilibrium. *Journal of Research in Science Teaching, 39*(8), 688-712.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *The American Journal of Physics, 50*(1), 66-71.

Crago, M. B., Eriks-Brophy, A., Pesco, D., & McAlpine, L. (1997). Culturally based miscommunication in classroom interaction. *Language, Speech, and Hearing Services in Schools, 28*(3), 245-254.

Cui, L., Zollman, D.A., & Rebello, N.S. (2005, April). Investigating introductory college students' knowledge of the particular nature of matter. Paper presented at the Annual Meeting of National Association for Research in Science Teaching, Dallas, TX.

Dawkins, R.K. (2003). Analyzing teachers' conceptions of ratio and proportion in the context of mass/mole relationships. Retrieved on March 13, 2004 from http://www.ncsu.edu/crmse/papers/analyzing_teachers_conceptions_of_ratio_and_proportion.htm

deGroot, A.D. (1978). *Thought and choice in chess.* The Hague, the Netherlands: Mouton.

de Vos, W. & Verdonk, A.H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching. 33*(6), 657-664.

diSessa, A. (1983). Phenomenology and the evolution of intuition. In D. Gentner and A. Stevens (Eds.), *Mental models*, (pp. 15-33). Hillsdale, NJ: Erlbaum.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman and P. Pufall (Eds.) *Constructivism in the computer age*, (pp. 49-70). Hillsdale, NJ: Erlbaum.

Dori, Y.J. & Hameiri, M. (2003). Multidimensional analysis for quantitative chemistry problems: Symbol, macro, micro, and process Aspects. *Journal of Research in Science Teaching. 40*(3), 278-302.

Duncan, I. M., & Johnstone, A. H. (1973). The mole concept. *Education in Chemistry, 10*(6), 213-214.

Easton, G. & Ormerod, T.C. (2001). Expert/Novice differences in case analysis, final report to European Case Clearing House. Retrieved on March 27, 2004 from http://www.ecch.cranfield.ac.uk/europe /pdffiles/ casemeth/research/lanc_toge.pdf.

Ebenezer, J.V., & Erickson, G. (1996). Chemistry students' conceptions of solubility. *Science Education*, *80*(2), 181-201.

Erickson, G.L. (1979). Children's conceptions of heat and temperature. *Science Education, 63*(2), 221-230.

Farmer, W. A., Farrell, M. A., Clark, R. M., & McDonald, J. (1982). A validity study of two paper-pencil tests of concrete and formal operations. *Journal of Research in Science Teaching, 19*(6), 475-85.

Felder, R. (1990). Stoichiometry without tears. *Chemical Engineering Education, 24*(4), 188-196.

Frank, D.V. & Baker A. C. (1987). Herron J.D., Should students always use algorithms to solve problems? *Journal of Chemistry Education*, *64*(6), 514-515.

Frazer, M.J. & Sleet, R.J. (1984). A study of students' attempts to solve chemical problems. *European Journal of Science Education, 6*(2), 141-152.

Friedel, A.W., Gabel, D.L. Samuel, J. (1990). Using analogs for chemistry problem solving: Does it increase understanding? *School Science and Mathematic*s, *90*(8), 674-682.

Friedel, A. W., & Maloney, D. P. (1992). An exploratory, classroom-based investigation of students' difficulties with subscripts in chemical formulas. *Science Education, 76*(1), 65-78.

Furio, C., Azcona, R., & Guisasola, J. (2002). The learning and teaching of the concepts 'amount of substance' and 'mole': A review of the literature. *Chemistry Education: Research and Practice in Europe, 3*(3), 277-292.

Furio, C., & Guisasola, J. (2000). Difficulties in teaching the concepts of 'amount of substance' and 'mole'. *International Journal of Science Education, 22*(12), 1285-1304.

Gabel, D., & Sherwood, R. (1979). The ACS-NSTA chemistry achievement exam: Beyond test results. *Journal of Chemical Education*, *56*(12), 813-814.

Gabel, D., & Sherwood, R. (1983). Facilitating problem solving in high school chemistry. *Journal of Research in Science Teaching*, *20*(2), 163-177.

Gabel, D., & Sherwood, R. (1984). Analyzing difficulties with mole concept tasksby using familiar analog tasks. *Journal of Research in Science Teaching*, *21*(8), 843-851.

Gabel, D., & Samuel, K. (1986). High school students' ability to solve molarity problems and their analog counterparts. *Journal of Research in Science Teaching*, *23*(2), 165-176.

Gabel, D. &. Bunce, D. M. (1994). Research on problem solving: Chemistry. In Gabel D., (Ed.), *Handbook of research on teaching and learning science*, (pp.301-326). New York,NY: Macmillan.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In: B.J. Fraser and K.G. Tobin (Eds.) *International handbook of science education,* (pp. 233-248). London, UK: Kluwer Academic Publishers.

Gardner, H. (1983). *Frames of mind: the theory of multiple intelligences.* New York, NY: Basic Books.

Gardner, H. (1987). The mind's new science: A history of the cognitive revolution: With a new epilogue, cognitive science after 1984. New York,NY: Basic Books.

Gardner, H. (1999). *Intelligence reframed: Multiple intelligences for the 21st century.* New York, NY: Basic Books.

Gendell, J. (1987). The solution is not the problem. *Journal of Chemical Education*, *64*(6), 523-524.

Genyea, J. (1983). Improving students' problem-solving skills. *Journal of Chemical Education, 60*(5), 478-482.

Georgiadou, A. & Tsaparlis, G. (2000). Chemistry teaching in lower secondary school with methods based on : A) Psychological theories; B) The macro, representational, and submicro levels of chemistry. *Chemistry Education: Research and Practice in Europe, 1*(2), 217-226.

Gerace, W.J. (2003). Problem solving and conceptual understanding. Retrieved on March 24, 2004 from http://piggy.rit.edu/franklin/PERC2001/ Gerace.doc

Glaser, R. & Chi, M. T. H. (1988). Overview. In M. T. H., Chi, R. Glaser, and M. J. Farr (Eds.), The nature of expertise, (pp. xv-xxviii). Hillsdale, NJ: Lawrence Erlbaum.

Goldberg, D.E. (2007). *Fundamentals of Chemistry.* New York, NY: McGraw-Hill Companies.

Gower, D.M., Daniels, D.J., & Lloyd, G. (1977). Hierarchies among the concepts which underlie the mole. *School Science Review, 59*(207), 285-299.

Griffiths, A.K., Kass, H., & Cornish, A.G. (1983). Validation of a learning hierarchy for the mole concept. *Journal of Research in Science Teaching, 20*(7), 639-654.

Green, B.F. (1966). Current trends in problem solving. In Kleinmuntz, (Ed.), *Problem solving: Research, method, and theory*, (pp. 3-18). New York,NY: John Wiley & Sons.

Green, S. B., & Salkind, N.J. (2003). *Using SPSS: Analyzing and understanding data.* Upper Saddle River, NJ: Prentice Hall.

Greene, J.C., Caracelli, V. J., and Graham, W. F. (1989). Toward a conceptual framework for mixed-method evaluation design. *Educational Evaluation and Policy Analysis*, *11*(3), 255-74

Hanson, D. & Wolfskill, T. (2000). Process workshops- a new model for instruction. *Journal of Chemical Education, 77*(1), 120-130.

Harrison, A.G. & Treagust, D.F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J.K. Gilbert et al., (Eds.), *Chemical education: Towards research-based practice*, (pp. 189-212). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Harrison, A.G. (2002). John Dalton's atomic theory: Using the history and the nature of science to teach particle concepts? Paper presented at the Annual Meeting of the Australian Association for Research in Education. Brisbane, Australia.

Hayes, J.R. (1981). *The complete problem solver*. Philadelphia, PA: Franklin Institute Press.

Herron, J.D. & Greenbowe, T.J. (1986). What can we do about Sue: A case study of competence. *Journal of Chemical Education*, *63*(6), 528-531.

Herron, J.D. (1978). Piaget in the classroom. *Journal of Chemical Education, 55*(3), 165-170.

Herron, J.D. (1975). Piaget for chemist: Explaining what good students cannot understand. *Journal of Chemical Education, 52*(3), 146-150.

Heyworth, R.M. (1999). Procedural and conceptual knowledge of expert and novice students for the solving of a basic problem in chemistry. *International Journal of Science Education*, *21*(2), 195-211.

Hoffmann, R., & Laszlo, R. (1991). Representation in chemistry. *Angewandte Chemie International Edition in English*, *30*(1), 1–16.

Howe, A.C., & Durr, B. (1982). Using concrete materials and peer interaction to enhance learning in chemistry. *Journal of Research in Science Teaching, 19*(3), 225-232.

Huddle, P.A., & Pillay, A.E. (1996). An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African University. *Journal of Research in Science Teaching, 33*(1), 65-77.

Huffman, D. (1997). The effect of explicit problem solving instruction on high school students' problem solving performance and conceptual understanding of physics. *Journal of Research in Science Teaching*, *34*(6), 551-570.

Huitt, W. (2003). The information processing approach to cognition. *Educational Psychology Interactive*. Valdosta, GA: Valdosta State University. Retrieved on February 28, 2005, from http://chiron.valdosta.edu/whuitt/col/cogsys/infoproc.html

Huitt, W., & Hummel, J. (2003). Piaget's theory of cognitive development. *Educational Psychology Interactive*. Valdosta, GA: Valdosta State University. Retrieved on February 27, 2005, from http://chiron.valdosta.edu/whuitt/col/cogsys/piaget.html.

Hunt, E. (1994). Problem solving. In Sternberg, R.J. (Ed.), Thinking and problem solving, (pp. 215-232). San Diego, CA: Academic Press.

Inhelder, B., & Piaget, J. (1964). *The early growth of logic in the child: classification and seriation.* New York, NY: W. W. Norton & Company Inc.

Jacobson, M.J. (2000). Problem solving about complex systems: Differences between experts and novices. In Fishman, B. & Divelbiss O. (Eds.), *Fourth international conference of the learning sciences*, (pp. 14-21). Mahwah, NJ: Erlbaum.

Johnstone, A. H., & Kellett, N. C. (1980). Learning difficulties in school science – Towards a working hypothesis. *European Journal of Science Education, 2*(2), 175 – 181.

Johnstone, A.H. (1983). Nyholm lecture: Chemical education research: Facts, findings, and consequences. *Journal of Chemical Education, 60*(11), 968-971.

Johnstone, A. H. (1984). New stars for the teacher to steer by. *Journal of Chemical Education*, *61*(10), 847 – 849.

Johnstone, A. H., & El–Banna, A. (1986). Capacities, demands and processes – a predictive model for science education. *Education in Chemistry*, *23*(5), 80 – 84.

Johnstone, A. H., & El–Banna, A., (1989).Understanding learning difficulties – A predictive research model. *Studies in Higher Education, 14*(5), 159 – 168,

Johnstone, A.H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*(2), 75-83.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemistry Education, 70*(9), 701 – 705.

Johnstone, A.H. (2001). Can problem solving be taught? *University Chemistry Education*, *5*, 69-73.

Kalantar, A. H. (1985). Limiting reagent problems made simple for students. *Journal of Chemical Education, 62*(2), 106.

Keret, Y. (2003). Adult proportional reasoning: Change processes in student teachers and teachers after exposure to " ratio and proportion". Retrieved on June 12, 2004 from http://www.tau.ac.il/education/toar3/archive/etakzir1999-3.html

Kintsch, W. (1970). *Learning, memory, and conceptual processes*. New York, NY: John Wiley & Sons.

Knight, R.D. (2002). Five easy lessons: Strategies for successful physics teaching. San Francisco, CA: Addison Wesley Publishing.

Kolb, D. (1978). Chemical principles revisited: The mole. *Journal of Chemical Education, 55*(11), 728-732.

Krishnan, S. R. (1994). The mole concept: Developing an instrument to assess conceptual understanding. *Journal of Chemical Education, 71*(8), 653-655.

Kwon, Y., Lawson, A.E., Chung, W., & Kim, Y. (2000). Effect on development of proportional reasoning skill of physical experience and cognitive abilities associated with prefrontal lobe activity. *Journal of Research in Science Teaching*, *37*(10), 1171-1182.

Larkin, J.H. (1979). Processing Information for effective problem solving. *Engineering Education, 70*(3), 285-288.

Larkin, J.H., McDermott, J., Simon, D.P., & Simon, H.A. (1980). Expert and novice performance in solving physics problems. *Science*, *208*, 1335-1342.

Larson, J. O. (1997). Constructing understanding of the mole concept: Interactions of chemistry text, teacher and learner. Paper presented at the *Annual Meeting of the National Association for Research in Science Teaching*. Oak Brook, IL.

Lawson, A. E., & Renner, J. W. (1975). Relationships of science subject matter and developmental levels of learners. *Journal of Research in Science Teaching, 12* (4), 347-358.

Lawson, A.E. (1979). Combining variables, controlling variables and proportions: Is there a psychological link? *Science Education, 63*(1), 67-72.

Lee, K.W.L. Tang, W.U., Goh, N.K. & Chia, L.S. (2001). The predicting role of cognitive variables in problem solving in mole concept. *Chemistry Education: Research and Practice in Europe, 2*(3), 285-301.

Lesh, R., Post, T., & Northern, M.B. (1988). Proportional reasoning. In J. Heibert & M.Behr (Eds.) *Number concepts and operations in the middle grades* (pp.93-118). Reston, VA: Lawrence Erlbaum & National Council of Teachers of Mathematics.

Lewis, E. L., & Linn, M. C. (1994). Heat energy and temperature concepts of adolescents, adults, and experts: Implications for curricular improvements. *Journal of Research in Science Teaching, 31*(6), 657-677.

Locke, J. (1995). *An essay concerning human understanding.* Amherst, NY: Prometheus Books.

Love, A., Stewart, J. L., & Kruger, A. C. (1996). Examining a coding scheme for a peer tutoring study: Agreement, reliability, or both? Paper presented at the *Annual Meeting of the Georgia Educational Research Association*. Atlanta, GA.

Lovell, R. (1961). A follow-up study of Inhelder and Piaget's the growth of logical thinking. *British Journal of Psychology, 52*(2), 143-153.

Lyle, K.S. & Robinson, W.R. (2001). Teaching science problem solving: An overview of experimental work. *Journal of Chemical Education, 78*(9), 1162-1163.

Mackenzie A. M, Johnstone, A. H., & Brown, R.F. (2003). Learning from Problem Based Learning. *University of Chemistry Education*, *7*(1), 13-26.

Maloney, D.P. (1994). Research on problem solving: Physics. In Gabel D., (Ed.), *Handbook of research on teaching and learning science*, (pp. 327-353). New York, NY: Macmillan.

Marshall, P.D. (2003). Expert-Novice differences in the application of accounting principles in solving accounting problems. Retrieved on April 20, 2004 from http://www.abe.villanova.edu/proc2000/n022.pdf.

Maskill, R., Cachapuz, A.F.C., & Koulaidis, V. (1997). Pages young pupils' ideas about the microscopic nature of matter in three different European countries. *International Journal of Science Education, 19*(6), 631-645.

Mayer, R.E. (1998). Cognitive, metacognitive, and motivational aspects of problem solving. *Instructional Science, 26*(1), 49-63.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner and A. Stevens (Eds.), *Mental models* (pp. 299-324). Hillsdale, NJ: Lawrence Erlbaum Associates.

McKinnon, J. W., & Renner, J. W. (1971). Are colleges concerned about intellectual development? *American Journal of Physics, 39*(9), 1047-1052.

Mettes, C. T.C.W., Pilot, A., & Kramers-Pals, H. (1980). Teaching and learning problem solving in science. *Journal of Chemical Education, 57*(12), 882-885.

Miller, G.A. (1994). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 101*(2), 343-352.

Minstrell, J. (1992). Facets of students' knowledge and relevant instruction. In R. Duit, F. Goldberg and H. Niedderer (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 110-128). Kiel, Germany: IPN.

Nakhleh, M.B., & Krajcik, J.S. (1991). The effect of level of information as presented by different technologies on students' understanding of acid, base, and pH concepts. Paper presented at the Annual Meeting of National Association for Research in Science Teaching, Lake Geneva, WI.

Nakhleh, M.B. (1993). Are our students conceptual thinkers or algorithmic problem solvers? *Journal of Chemical Education, 70*(1), 52-55.

Nakhleh, M. B. and Mitchell, R. C. (1993). Concept learning versus problem solving: there is a difference. *Journal of Chemistry Education*, *70*(3), 190-192.

Nakhleh, M.B., Lowrey, K.A., & Mitchell, R.C. (1996). Narrowing the gap between concepts and algorithms in freshman chemistry. *Journal of Chemistry Education, 73*(8), 758-762.

Niaz, M. (1988). Manipulation of M-demand of chemistry problems and its effect on student performance: A neo-Piagetian study. *Journal of Research in Science Teaching, 25*(8), 643-657.

Niaz, M. (1989). The relationship between M-demand, algorithms, and problem solving: A neo-Piagetian study. *Journal of Chemistry Education, 66*(5), 422-424.

Niaz, M. (1994). Progressive transitions from algorithmic to conceptual understanding in student ability to solve chemistry problems: A Lakatosian interpretation. Paper presented at the Annual Meeting of National Association for Research in Science Teaching, Anaheim, CA.

Nickerson, R.S. (1994). The teaching of thinking and problem solving. In Sternberg, R.J. (Ed.) *Thinking and problem solving* (pp. 419-441). San Diego, CA: Academic Press, Inc.

Nieswandt, M. (2001). Problems and possibilities for learning in an introductory chemistry course from a conceptual change perspective. *Science education*, *85*(2), 158-179.

Novick, S. and J. Nussbaum. 1981. Pupils' understanding of the particulate nature of matter: A cross-age study. *Science Education, 65*(2), 187-196.

Nurrenbern, S. C. and Pickering, M. (1987). Concept learning versus problem solving: is there a difference? *Journal of Chemistry Education*, *64*(6), 508-510.

Opdenacker, C., Fierens, H., Van Brabant, H., Sprut, J., Slootmaekers P. J., &Johnstone, A. H. (1990). Academic performance in solving chemistry problems related to student working memory capacity. *International Journal of Science Educatio*n, *12*(2), 177 – 185.

Osborne, R.J., & Cosgrove, M.M. (1983). Children's conceptions of the changes of state of water. *Journal of Research in Science Teaching, 20*(9), 825-838.

Pandey, N.N., Bhattacharya, S.B., & Rai, V.K. (1993). Longeot test of cognitive development in Indian context. *Studies in Educational Evaluation, 19*(4), 425-430.

Pasceralla, A. (2004). CAPA (Computer-Assisted Personalized Assignments) in a large university setting. Retrieved on April 13, 2004 from http://www.physics.uni.edu/~pascarel/Research/Thesis/ChapterTwo.pdf

Perez, G.D., & Torregrosa, J.M. (1983). A model for problem-solving in accordance with scientific methodology. *European Journal of Science Education*, *5*(4), 447-455.

Perkins, D.N., & Salomon, M. (1989). Are cognitive skills context-bound? *Educational Researcher*, January-February, 16-25.

Pestel, B. (1993). Teaching problem-solving without modeling through "thinking aloud pair problem solving". *Science Education, 77*(1), 83-94.

Phelps, A.J. (1996). Teaching to enhance problem solving: It's more than the numbers. *Journal of Chemical Education*, *73*(4), 301-304.

Piaget, J. (1950). *The psychology of intelligence* (M. Percy & D.E. Berlyne, translators). London, NY: Routledge & Kegan Paul.

Pinarbasi, T., & Canpolat, N. (2003). Students' understanding of solution chemistry concepts. *Journal of Chemical Education, 80*(11), 1328-1332.

Plesch, P. (2004). On the distinctness of chemistry. *Foundations of Chemistry, 1*(1), 6-15.

Polya, G. (1945). *How to solve it*. Princeton, NJ: Princeton University Press.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Towards a theory of conceptual change. *Science Education, 66*(2), 211-227.

Potvin, P. (2005, April 3-8). The use of explicitation interview in the study of (non-) scientific conceptions. Paper presented at the *Annual Meeting of the National Association for Research in Science Teaching*, Dallas, TX.

Reif, F., & Heller, J.I. (1982). Knowledge structure and problem solving in physics. *Educational Psychologist, 17*(2), 102-127.

Reif, F. (1983). How can chemist teach problem solving? *Journal of Chemical Education, 60*(11), 948-953.

Reif, F. (1987). Instructional design, cognition, and technology: Applications to the teaching of scientific concepts. *Journal of Research in Science Teaching*, *24*(4), 309-324.

Robinson, W.R. , & Niaz, M. (1991). Performance based on instruction by lecture or by interaction and its relationship to cognitive variables. *International Journal of Science Education, 13*(2), 203-215.

Robinson, W.R. (2003). Chemistry problem-solving: Symbol, macro, micro, and process aspects. *Journal of Chemical Education*, *80*(9), 979-982.

Ross, M. R.; Fulton, R. B. (1994). Active learning strategies in the analytical chemistry classroom. *Journal of Chemical Education*, *71*(2), 141-143.

Ryan, J. N. (1987). The name's the game in problem solving. *Journal of Chemical Education*, *64*(6), 524-525.

Sanchez, K. & Betkouski, M. (1986). A study of factors affecting student performance in community college general chemistry course. Paper presented at the *Annual Meeting of the National Association for Research in Science Teaching*. San Francisco, CA.

Sawrey, B. (1990). Concept learning vs. problem solving: Revisited. *Journal of Chemical Education, 67*(3), 253-54.

Scandura, J. M. (1977). Problem solving: A structural and process approach with instructional implications. London, UK: Academic Press, Inc. Ltd.

Schmidt, H.J., & Jigneus, C. (2003). Students' strategies in solving algorithmic stoichiometry problems. *Chemistry Education: Research and Practice, 4*(3), 305-317.

Schmidt, H.J. (1997). An alternate path to stoichiometric problem solving. *Research in Science Education*, *27*(2), 237-249.

Segal, E. (2005). Expertise and its development. Retrieved on March 2, 2005, from http://pluto.fss.buffalo.edu/classes/psy/segal/416f2001/Expertise.htm.

Sheehan, D. (1970). The effectiveness of concrete and formal instructional procedures with concrete and formal operational students. Unpublished doctoral dissertation. State University of New York, Albany.

Shiffrin, R., & Nosofsky, R. M. (1994). Seven plus or minus two: A commentary on capacity limitations. *Psychological Review, 101*(2), 357-361.

Silberberg, M.S. (2006). *Chemistry: The molecular nature of matter and change*. 4th Edition. New York, NY: McGraw-Hill Companies.

Sirhan, G., Gray, C., Johnstone, A. H., & Reid, N. (1999). Preparing the mind of the learner. *University of Chemistry Education*, *3*(2), 43- 46.

Smith, P. J., & Van Egeren, T. (1977). Piagetian principles used in a highschool chemistry class. Paper presented at the national meeting of the American Chemical Society, New Orleans, Louisiana.

Smith, M.U. & Good, R. (1984). Problem-solving and classical genetics: successful versus unsuccessful performance. *Journal of Research in Science Teaching*, *21*(9), 895-912.

Smith, M. U. (1992). Expertise and the organization of knowledge: Unexpected differences among genetic counselors, faculty, and students on problem categorization tasks. *Journal of Research in Science Teaching*, *29*(2), 179-205.

Smith, M.U., & Sims, O.S. (1992). Cognitive development, genetics problem solving, and genetics instruction: A Critical Review. *Journal of Research in Science Teaching, 29*(7), 701-713.

Stamovlasis, D., & Tsaparlis, G. (2000). Non-linear analysis of the effect of working-memory capacity on organic-synthesis problem solving. *Chemistry Education: Research and Practice in Europe*, *1*(3), 375-380.

Staver, J.R., & Lumpe, A. T. (1995). Two investigations of students' understanding of the mole concept and its use in problem solving. *Journal of Research in Science Teaching, 32*(2), 177-193.

Sternberg, R.J. (2001). Teaching problem solving as a way of life. In A. Costa (Ed), *Developing Minds: A Resource Book for Teaching Thinking Third Edition (pp. 451-454).* Alexandria, VA: Association for Supervision and Curriculum Development.

Stieff, M. (2004). An emergent modeling environment for teaching and learning chemistry. Retrieved on March 27, 2004 from http://ccl.northwestern.edu/papers/chemlogo

Stiff, L.V. (1988). Problem solving by example. *School Science and Mathematics*, *88*(8), 666-675.

Taconis,, R., Ferguson-Hessler, M.G.M., & Broekkamp, H. (2001). Teaching science problem solving: An overview of experimental work. *Journal of Research in Science Teaching, 38*(4), 442-468.

Thagard, P. (1992). *Conceptual revolutions*. Princeton,NJ: Princeton University Press.

Tingle, J.B., & Good, R. (1990). Effects of cooperative grouping on stoichiometric problem solving in high school chemistry. *Journal of Research in Science Teaching, 27*(7), 671-683.

Tobin, G.T. & Capie, W. (1981). The development and validation of a group test of logical thinking. *Educational and Psychological Measurement*, *41*(2), 413-423.

Towns, M. & Grant, E. (1998). "I believe I will go out of this class actually knowing something": Cooperative learning activities in physical chemistry. *Journal of Research in Science Teaching. 34*(8), 819-835.

Trifone, J. D. (1987). The test of logical thinking. *The American Biology Teacher, 49*(8), 411-416.

Tsaparlis, G., & Angelopoulos, V. (2000). A model of problem solving: Its operation, validity, usefulness in the case of organic-synthesis problems. *Science Education, 84*(2), 131-153.

Tsaparlis, G., Kousathana, M., & Niaz, M. (1998). Molecular equilibrium problems: Manipulation of logical structure and M-demand, and their effect on students' performance. *Science Education, 82*(4), 437-454.

Tuncer, Y. (2003). Turkish pupils' conceptions of the conservation of mass during the phase changes. *Science Education International. 14*(3), 14-20.

Valanides, N. (2000). Primary student teachers' understanding of the particulate nature of matter and its transformations during dissolving. *Chemistry Education: Research and Practice in Europe, 1*(2), 249-262.

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education, 1*(2), 205-221.

Vosniadou, S., & Brewer, W.F. (1992). Mental models of the earth: A study conceptual change in childhood. *Cognitive Psychology, 24*(4), 535-585.

Vosniadou, S. (1994) Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*(1), 45-69.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1993). Research on alternative conceptions in science. In D. L. Gabel (Ed.), *Handbook of research on science teaching and learning: A project of the national science teachers association* (pp. 177-210). New York, NY: Macmillan.

Ward, C., & Herron, J. (1980). Helping students understand formal chemical concepts. *Journal of Research in Science Teaching, 17*(5), 387-400.

Ward, C., & Nurrenbern, S.C., Lucas, C., & Herron, J.D. (1981). Evaluation of the Longeot test of cognitive development. *Journal of Research in Science Teaching, 18*(2), 123-130.

Watson, J.R. & Boo, H. K. (2001). Progression in high school students' (aged 16-18) conceptualizations about chemical reactions in solution. *Science Education*, *85*(5), 568-585.

Wenning, C.J. (2003). A multiple case study of novice and expert problem solving in kinematics. Retrieved June 13, 2003, from http://www.phy.ilstu.edu/faculty/wenning/ptefiles/311content/probsolving/expertnovice.html

Wheeler, A., & Kass, H. (1977). *Proportional reasoning in introductory high school chemistry.* Cincinnati, OH: National Association for Research in Science Teaching.

Whimbey, A. (1984). The key to higher order thinking is precise processing. *Educational Leadership, 42*(1), 66-70.

Williamson, V., Huffman, J., & Peck, L. (2004). Testing students' use of particulate theory. *Journal of Chemical Education. 81*(6), 891-896.

Wilson, W.J., Fernandez, M.L., Hadaway, N. (2003). Mathematical problem solving. Retrieved on July 23, 2003, from http://jwilson.coe.uga.edu/emt725/PSsyn/PSsyn.html

Wolfer, A.J., & Lederman, N.G. (2000). Introductory college chemistry students' understanding of stoichiometry: Connections between conceptual and computational understandings and instruction. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Woods, D.R., Crowe, C.M., Hoffman, T.W., & Wright, J.D. (1979). Major challenges to teaching problem-solving skills. *Engineering Education,* December*,* 277-284.

Woods, D.R. (1987). How might I teach problem solving? In Stice, J.E. (Ed.), Developing Critical Thinking and Problem Solving Abilities (pp. 55-71). *New Directions for Teaching and Learning*, 30. San Francisco, CA: Jossey-Bass.

Woods, D.R. (1989). Developing students' problem-solving skills. *Journal of College Science Teaching*, *19*(3), 176-179.

Wu, H.-K., Krajcik, J. S., & Soloway, E. (2001). Promoting conceptual understanding of chemical representations: students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching, 38*(7), 821-842.

Wu, H. (2003). Linking the microscopic view of chemistry to real-life experiences: Intertextuality in a high-school science classroom. *Science Education*, *87*(6), 868-891.

Yalcinalp, S., Geban, O, & Ozkan, I. (1995). Effectiveness of using computer-assisted supplementary instruction for teaching the mole concept. *Journal of Research in Science Teaching, 32*(10), 1083-1095.