High School Students' Problem Solving Approaches on the Concept of Stoichiometry

Hyun-Ju Park
(Chosun University)

ABSTRACT

This study examined two students' problem solving approaches: the similarities and the differences in their problem solving approaches, and the general problem solving strategies (heuristics) the students employed were discussed. The two students represent differences not only in terms of grades earned, but also in terms of participation, motivation, attention to detail, and approaches to answering questions and problem solving. Three separate problems were selected for this study: A stoichiometry problem; a fruit salad problem; and a limiting reactant problem. Each student was asked individually on three separate occasions to contribute to this study. There are more similarities in the students' problem solving strategies than there are differences. Both students were able to correctly solve the stoichiometry and the fruit salad problems, and were unable to correctly solve the limiting reactant problem. They recognized that an algorithm could be used for both chemistry problems(a stoichiometry problem & a limiting reactant problem). Both students were unable to correctly solve the limiting reactant problem and to demonstrate a clear understanding of the Law of Conservation of Mass. Nor did they show an ability to apply it in solving the problem. However, there was a difference in each one's ability to extend what had been learned/practiced/quizzed in class, to a related but different problem situation.

Key words: problem solving, stoichiometry, diversity, problem solving strategies

I. Introduction

Helping students develop problem solving skills is a frequently cited goal of science educators. Science teachers help students learn and think logically, specifying that "... high school laboratory and field activities should emphasize not only the acquisition of knowledge, but also problem solving and decision making"(NSTA, 1985).

Problem solving means many things to many people. For some, it includes an attitude or predisposition toward inquiry, as well as the actual processes by which individuals attempt to gain knowledge(Ambruso, 2003). Usually, when teachers discuss problem solving with their students, the anticipant students will become involved with the thinking operations of analysis, synthesis, and evaluation (considered as higher-level thinking skills)(Lee, 1982).

Research on problem solving in the 1960's was focused on how students solve puzzles and games, and science education researchers in the 1970's tape recorded 'think aloud' interviews, to gather data and to understand how to solve problems (Good & Smith, 1987). Current research

*Received on 01 June 2004 **Hyun-Ju Park (hjapark@mail.chosun.ac.kr)
***This study was supported (in part) by research funds from Chosun University, 2003.

on problem solving in science education involves information processing theory(Gendel, 1987; Kean, Middlecamp, & Scoot, 1988) - the idea that solving a problem requires two processes: retrieval from memory of the pertinent information, and proper application of the information to the problem. Research studies published nowadays are frequently comparisons of expert and novice problem solvers in science, and of the diversity of students in problem solving processes (Herron, 1975; McCalla, 2003).

Every classroom of students exhibits diversity. This diversity may be expressed in terms of academic abilities, modes of learning, motivation for learning, and interests, among many other things(Tobias, 1990; Wilson, 1992). In order to be successful, teachers need to become aware of the diversity that exists in their students. Being aware of this diversity allows teachers to adjust and plan instructional activities(Kim, Yeo, & Woo, 1999) that can more appropriately meet the learning needs of all students in their classes(Asirvatham, 2004).

The purpose of this study was to examine the problem solving approaches of two students from the chemistry classes. After comparing the problem solving approaches from a first year high school science class on three separate problems presented to them, the similarities and the differences in their problem solving approaches, and the general problem solving strategies (heuristics) the students employed, are delineated.

Ⅱ. Research Methods

1. Participants

In this study, there were two students who were representative of the diversity that exists in high school science classes. The two students represent differences, not only in terms of grades earned, but also in terms of participation, motivation, attention to detail, and approaches to answering questions and problem solving.

Miwon is an 11th grader who is very willing to answer questions and participate in class discussions. She works intently in class, but has turned in incomplete or late homework on occasion. Miwon has difficulty in recalling the information and problem solving processes that have been discussed and practiced in class. Her test average is in the 'C' range of the grading scale. Additionally, alternative approaches and alternative conceptual ideas are displayed by Miwon on some of her homework and lab activities. She tends to develop her own method, or use a combination of approaches when working on problems which challenge her.

Jaymin is also an 11th grader, but who tends to be quieter in terms of class participation. She typically remains reserved, 'soaking' everything in that her teacher and classmates are saying. Jaymin is very conscientious about her grades in chemistry. She has never handed in a late or incomplete assignment. She effectively recalls information and problem solving processes which have been covered in class. Her test average is in the upper 'B' to lower 'A' range of the grading scale. Jaymin works very quickly and efficiently in class, often finishing assignments and tests in advance of her classmates.

2. Problems Selected

Three separate problems(Carson-Dellosa Publishing, 1994) were selected for this study(See

Appendix). The first problem was a stoichiometry problem in which the students were asked to determine the number of grams of one reactant needed to completely react with a given number of grams of another reactant. The balanced chemical equation was provided. Students showed a step by step method for solving stoichiometry problems. The second problem presented to the students was a fruit salad problem, unrelated to chemistry, which required unit conversions in order to arrive at the solution. The fruit salad problem does bear a resemblance to chemical equations in that the relationship between oranges and apples to make fruit salad could be represented by the following: 5 oranges + 8 apples → 2 batches of fruit salad. The third problem was best identified as a limiting reactant problem. The stoichiometry problems that the students had been exposed to always stated that one reactant was in excess, or that they were to assume that the given reactant was completely reacted.

3. Data Gathering and Analysis

Each student was asked individually on three separate occasions to contribute to this study. The first session lasted approximately 15 minutes for each student. It was designed to help the student become comfortable and familiar with the method of interview. The main problem solving session lasted approximately 45 minutes for each student. The students were asked to read the problem, out loud, and then say what they were thinking as they worked on the problem. The students were also asked to write down their work in the space provided on the paper below each problem. Both students did an excellent job of keeping on task and continuing to talk through all three problems. Each student was occasionally inventive by asking conceptual questions during the stoichiometry and limiting reactant problems. For example, both students were asked to explain what the 'mole' represented and why they had to use that in the problem. Also, both students were asked to draw a picture to represent the balanced equation in the stoichiometry problem, i.e., to show what the molecules would look like. Both students reached a point while working on the limiting reactant problem, in which they felt they had exhausted all of their options.

The entire audio-taped protocol from their problem solving was transcribed for both students. Each transcript was thoroughly read and analyzed for answers to the research questions.

Ⅲ. Results and Discussions

The two high school students' problem solving approaches are summarized as: the similarities, the differences in the problem solving protocols of the two students, and the general problem solving strategies (heuristics) employed by each student as they worked on the three problems presented to them.

1. Similarities

In comparing the high school students' problem solving approaches on three separate problems, the similarities are classified into three categories: Both students were able to; were unable to; and were metacognitive. First, both Jaymin and Miwon were able to relate the mole to grams on the periodic table, the mole to coefficients of the balanced chemical equation. They stated the mole/number ratio from the balanced chemical equation. They successfully drew an appropriate picture representation showing the number of molecules reacting/forming for the balanced chemical equation given in the stoichiometry problem: $3H_2 + N_2 \rightarrow 2NH_3$. They also recognized that an algorithm (grams given → moles given → moles needed → grams needed) could be used for both chemistry problems (stoichiometry and limiting reactant). Therefore, they 'correctly' solved problem 1 (stoichiometry), even though each used a different approach.

Second, both students were unable to 'correctly' solve the limiting reactant problem. They didn't demonstrate a clear understanding of the Law of Conservation of Mass and an ability to apply it in solving the chemistry problems. They couldn't recognize that 5 oranges plus 8 apples yields 2 batches of fruit during the first question of the fruit salad problem. Both mentioned that 9 batches would be made in this first question; however, both also correctly answered 18 batches when asked directly to find the number of batches made in question 5 of the fruit salad problem.

Third, both students were metacognitive. Metacognition refers to instances in which individuals reflect on their own learning, or think about their own thought processes. During the stoichiometry problem, Miwon displayed metacognition when she said, "I'm Jumping ahead here. Need the... Grams... Okay... Yeah, I'm jumping the gun on this one". During the stoichiometry problem (3 times), the fruit salad problem (1 time), and the limiting reactant problem (7 times), she talked about the thoughts going through her mind as was evidenced by statements in which she began by saying "I'm thinking that..." Of course, some of this evidence for metacognition on the part of the students, was influenced by the fact that the students were asked to think out loud as they worked on the problems. However, prefacing a statement by saying, "I'm thinking that..." indicated a different level of thought in some cases where perhaps one was struggling with which way to approach a problem, or trying to evaluate their own thinking(Rief & Larkin, 1991).

Jaymin also prefaced statements during the fruit salad problem (1 time) and the limiting reactant problem (7 times) by saying "I'm thinking that..." or "I think..." She appeared to be less metacognitive during the stoichiometry problem, probably because she solved this problem very quickly through the application of the factor-label algorithm.

2. Differences

Jaymin was more familiar with the terminology that had been discussed and used to work stoichiometry problems in class. She was able to more clearly define what a mole actually was during the stoichiometry problem. She correctly used the labels, mole and grams per mole, throughout her work on both chemistry problems. Jaymin recognized immediately that an algorithm might be used in the stoichiometry problem and applied it correctly to obtain an answer to the problem. After a lengthy pause upon initially reading the limiting reactant problem, she also applied the factor-label algorithm to arrive at an answer. However, in this case, her answer was incorrect because she failed to first determine which substance was the limiting reactant. She chose the wrong substance (calcium) to start with, based upon it being listed first in the problem, and because the 50 grams given for calcium was an easier number to work with.

Miwon mentioned in both the stoichiometry problem and the limiting reactant problem that

Table 1. Similarities in the problem solving protocols

Both students were able to:

- Relate the mole to grams on the periodic table (Miwon never defines mole in this way)
- Relate the mole to coefficients of the balanced chemical equation
- State the mole/number ratio from the balanced chemical equation
- Draw an appropriate picture representation for the balanced chemical equation given in the stoichiometry problem: $3H_2 + N_2 \rightarrow 2NH_3$
- Recognize that an algorithm (grams given → moles given → moles needed → grams needed) could be used for both chemistry problems (stoichiometry and limiting reactant)
- "Correctly" solve problem #1 (stoichiometry) (each uses a different approach) - "correctly" solve the fruit salad problem and make the necessary conversions

Both students were unable to:

- "Correctly" solve the limiting reactant problem [both spent the longest amount of time on this problem]
- Demonstrate a clear understanding of the Law of Conservation of Mass and an ability to apply it in solving the chemistry problems (1 & 3)
- Recognize that 5 oranges plus 8 apples yields 2 batches of fruit during the first question of the fruit salad problem (both mentioned that 9 batches would be made in this first question; however, both also correctly answered 18 batches when asked directly to find the number of batches made in question 5 of the fruit salad problem)

Both students were metacognitive

Miwon

Problem 1 - States, *"I'_ jumping ahead here. Yeah, I'_ jumping the gun on this one"*
- Double checks answer using another approach

Problem 3 - Talks about the thoughts that she was contemplating when working on this problem, especially when she is asked to compare her work to an incorrect and a correct solution to the problem

Jaymin

Problem 1 & 2 - Actually changes initial answers/calculations on 4 occasions after realizing that they are incorrect (too high, don' t match to knowledge stored in memory)

Problem 3 - Double checks calculations on two occasions
- Wonders if numbers/calculations were done correctly

some type of equation or conversion process could be used. She even mentioned the "grams to moles and moles back to grams" algorithm during the stoichiometry problem. During work on the limiting reactant problem, she turned it around and stated "moles to grams and grams back to moles". She was unable to apply the algorithm to either problem. The fact that she turned around the words when mentioning the algorithm indicates that she was unable to recall exactly what it was. In other words, it might not be part of her working knowledge.

Miwon incorrectly used the label grams per mole six times during the stoichiometry problem, and incorrectly used the label mole three times during both of the chemistry problems. She seemed unclear on the definition of the mole. She never stated a definition and used the term incorrectly when working number comparisons from the problem to the Periodic Table. However, she was able to relate the mole to the coefficients from the balanced chemical equation.

Most of all, Jaymin got hung up on the misconception that there was some weight (mass) loss due to energy being released in this problem, and was never able to discard this idea, even when presented with a 'correct' solution to look over during the follow-up questioning session. Jaymin recalled and stated the Law of Conservation of Mass during the limiting reactant problem, but did not apply it. Miwon never explicitly stated this law, but actually applied it to obtain an answer for the stoichiometry problem. However, during the limiting reactant problem, she firmly expressed the idea that some weight (mass) was lost in energy which runs directly counter to this law.

Table 2. Differences in the problem solving protocols

Miwon	Jaymin
- Mentions that an algorithm (grams moles → moles → grams) could be used for both of the chemistry problems (1 & 3) but doesn't remember the steps involved in its use, and is unable to apply it	- Immediately recalls the algorithm (grams given → moles given → moles needed → grams needed) and uses it to correctly determine the answer to the stoichiometry problem
- Incorrectly states that the algorithm is moles → grams → grams → moles during chemistry problem #3 - Does not employ an algorithm while working on either chemistry problem; instead calculates the grams per mole for each substance and compares by relating to the balanced chemical equation coefficients	- In spite of being unsure at first, still employs the algorithm (grams given → moles given → moles needed → grams needed) on calcium only in the limiting reactant problem; obtains an incorrect answer because calcium is not the limiting reactant
- Struggles to come up with an answer to the stoichiometry problem (#1). Uses 'hill climbing' and 'means-ends analysis' (Problem solving techniques and algorithms, 2004) to eventually come up with an answer expressed in confidence	- Reflects and goes back to change miscalculated numbers in the stoichiometry problem and the fruit salad problem
- Incorrectly uses the label "grams per mole" a total of 6 times in chemistry problem #1(stoichiometry)	- Correctly refers to and uses the labels grams per mole and mole throughout both chemistry problems
- Uses the term "mole value" or "molar value" in place of "grams per mole" a total of 6 times	
- Incorrectly uses the label "mole" 3 times	
- Incorrectly states the number of moles present of a given substance upon comparison with the formula mass on the Periodic Table once during each chemistry problem (e.g. states a little under one mole when it actually should be a little over one mole)	
- Never states that one mole is equal to the atomic weight (gram-formula mass) for the elements or compounds [seems unclear on mole definition]	
- Mentions early on the correct answer to the limiting reactant problem but doesn't recognize it as such; eventually gives up on the problem	

Table 2. Differences in the problem solving protocols (continued)

Miwon	Jaymin
- Never expresses the idea for the limiting reactant problem that one reactant may be in excess in spite of follow-up questioning and redirection	- Expresses the notion that one reactant is in excess for the limiting reactant problem and determines the approximate amount in excess only after follow-up questioning and redirection
- Uses the Law of Conservation of Mass (without explicitly stating it) to get an answer to the stoichiometry problem: however holds onto a misconception related to this law while working on the limiting reactant problem	- States the Law of Conservation of Mass while working on the limiting reactant problem but is not sure if its use would be appropriate; cannot think of this law when asked to find the mass of the product as a follow-up question to the stoichiometry problem
- Misconception: Insists a total of 7 times during the limiting reactant problem that there must be some weight loss which is converted into energy. She is unable to clearly explain her ideas on why this happens. Does not mention this weight loss/energy release while working on the stoichiometry problem	- Major Assumption: Chose to use 50grams of calcium instead of 32grams of sulfur as the starting point in applying the factor label algorithm for the limiting reactant problem - Reason given: the calcium was listed first and 50 was an even number
This misconception persists even when Miwon is allowed to look at the correct solution to the limiting reactant problem	This was possibly a guess by Jaymin as she seemed unable to think of anything else to do; maybe she was influenced by her experience with typical textbook and classroom problems which use 'nice and even' numbers

3. General problem solving strategies (heuristics)

Looking over the information gathered in Table 3, it is easy to see that there are more similarities in the students' problem solving strategies than there are differences. Both students employ a means-ends analysis for all three problems for at least part of their work. Trial and error, and rereading the problem, are used by both in the limiting reactant problem. They break the fruit salad questions into parts, in order to develop their final answers.

Both students checked and verified their answers. During the follow-up questioning on the limiting reactant problem, Jaymin wondered if the numbers she had used were correct, and double checked her calculations twice. Miwon also double checked her calculation of the grams per mole for calcium sulfide while working on this problem. Twice during the stoichiometry problem, and twice during the fruit salad problem, Miwon went back and changed initially calculated numbers upon realizing that the numbers she had come up with did not make sense. Each of these cases is an example of employing the general heuristic of checking interim answers against information held in memory. Although there was not enough data on whether Miwon employed this particular heuristic, she did exhibit verification abilities at the end of her work on the stoichiometry problem. First, she found an answer by subtracting the molar mass of nitrogen (28.02) from twice the molar mass of ammonia (34.08) to get 6.06 grams for the hydrogen. Then she went on to state :

It's 6.06 grams per mole and that looks to be correct. Because hydrogen, the value for hydrogen is 1.01 and we have 2 of those which would leave it 2.02 and there are 3 moles of it ···· which would put it at 6.06 grams per mole. And that's what we're looking for, so how many grams of hydrogen is 6.06 grams of hydrogen.

Miwon(M) was allowed to look at, and compare, both an incorrect and a correct solution to the limiting reactant problem. Although she was able to identify the correctly worked out solution as being representative of the correct answer, she was still persistent on her ideas that there was some mass lost due to energy being given off.

M – I think the second sheet is the one that's closer to what I was thinking because ···· I knew that the mole value ···· I was looking at the mole value, the 72.13 grams per mole ····was close and I kept saying that some were lost in energy.

T – Okay.

M – And when you worked it out at the very bottom here ..0.998 times the one mole of calcium sulfide times the 72.14 you came up with 72.0 ···· that .14 grams is what I was looking for given off in energy.

T – Okay so you feel ····

M – I feel that one's closer to what I was trying to come up with.

T – Okay.

M – Because it would explain the loss of energy involved.

Miwon had a more difficult time with the stoichiometry problem. She struggled to find a means to obtain an answer. During this struggle, she utilized different approaches and, therefore, had a longer list of heuristics for this problem. Jaymin, on the other hand, immediately recognized a path to the solution (the factor-label algorithm) and used it to solve the problem very quickly. For her, the stoichiometry problem was an exercise rather than a problem (for which she would not have immediately known how to find the answer). There was only one heuristic, when checking interim results against information held in memory, which I found evidence for being used by Jaymin, but not by Miwon. Jaymin(J) was able to correct her initially calculated numbers for the grams per mole for N_2 and H_2, when she realized that the numbers did not match with the formulas.

J – So I start out with 28 grams of nitrogen and you multiply that times one mole times the atomic weight of nitrogen which is 14.01. And then multiply that over ···· one . .okay, times 3 moles of hydrogen over one ···· one mole of nitrogen. And then ···· you ···· one over H_2 which is 1.01.Oh wait, it'd be 2.02 grams. Okay, I'm going to change this one over here to 28.02.

T – Okay, can you tell me why you are doing that?

J– That was nitrogen. 'Cause it's N_2 instead of just N. I'm going to change that over. So then it's 28 divided by 28.02 times 3 times 2.02 and I got 6.06 grams of the hydrogen for the answer.

Jaymin made a similar correction during the fruit salad problem, when an initial number arrived at during work on the problem was calculated incorrectly using the calculator. She realized it was way too high, when compared to another number she had calculated that was to be added to it. The ability of Jaymin to recognize and make these corrections demonstrates that she possessed enough knowledge (i.e., information held in memory) to know whether a calculated number made sense, and that she could access this knowledge.

Jaymin demonstrates a conceptual understanding which is closer to the accepted scientific view than Miwon does. An easily identifiable misconception that was held very firmly by Miwon was that there must be some weight (mass) loss due to energy being released. She only mentioned this during the limiting reactant problem, but did so a total of 7 times in just this one problem. When asked to explain why there was a loss of mass due to energy, she was unable to explain it clearly, and was very unsure of what it resulted from.

M – I don't think the 72.13 grams per mole is the correct amount on the calcium sulfide.
T – And why do you say that?
M – Might be ···· umm ···· I don't think it is because there has to be some energy loss somewhere that has to be accounted for. And therefore when you add the two numbers together, when you add the calcium, the moles of calcium and the moles of sulfur you get 72.13. And with the energy loss that's not the correct amount.
T – How does the energy affect the amount?
M – It shouldn't ···· If it's given off in heat or ···· uum. This a solid so no gas is given off. So if it's giving off energy it's losing ···· some of the ····of the molecules down at the molecular level, so therefore the weight would be ···· the overall weight would be off (long pause).
T – Any more thoughts on this?
M – No. I just can't think of how you would work that out.

Even when Miwon was shown the correct solution to the limiting reactant problem, she still insisted there is some loss of mass due to energy being given off. Why did Miwon insist that there must be some energy loss accompanied by a loss of mass for this problem? It might relate to a caloric view of heat which believes that heat was a matter-like entity that could be released or absorbed. This was a view held by early scientists who attempted to explain the concept of heat(Kean *et al.*, 1988).

This misconception might also have arisen from information Miwon had been taught regarding nuclear reactions. In nuclear reactions, there was a small amount of mass lost which was accompanied by a large amount of energy released, according to Einstein's famous equation, $E = mc^2$. Nuclear reactions were discussed briefly in science class at the beginning of the school year.

Jaymin had greater ability to extend what has been learned/practiced/quizzed in class to a related but different problem situation than Miwon. The limiting reactant problem presented a new situation to both students, which was related to the stoichiometry problems. Interestingly, it was Jaymin who came the closest to expressing a confident, corrected answer to this problem. Very early on, she compared the mole ratio of the substances in the equation, and figured the grams per mole for calcium sulfide. She mentioned a 72.13 grams per mole figure, but did not recognize it as being the correct answer.

Okay, so we know that there are 50 grams of calcium and 32.0 grams of sulfur. And we're trying to find out how much calcium sulfide is made in grams. You can't just add 'em up and get 82.0 grams because some of that weight is always lost in energy. So you can't add'em together. Hmm ...

> So we have a little more than 1 mole of calcium and we have just a little more than 1 mole, almost exactly one mole of sulfur. So we'd have, we should have almost exactly one mole of calcium sulfide. I got that by looking at the weight that we have of the calcium which is 50.0 grams and on the periodic table it's 40.08 grams per mole. And for the sulfur is 32.06 grams per mole ···· And so the total mole ratio should be ···· should be 72.13 grams per mole for the calcium sulfide.
> Umm ···· grams . . calcium sulfide . . equal ····

Jaymin paused for an extended period of time after reading the limiting reactant problem before deciding to start with calcium's mass. She then employed the factor-label algorithm to compute the mass of the calcium sulfide produced. However, sulfur happened to be the limiting reactant, not calcium. When asked why she chose the calcium, and not the sulfur, she replied because it was listed first. The following excerpt from Jaymin's problem solving protocol also shows the point where she expressed uncertainty as to whether the Law of Conservation of Mass could be applied in the limiting reactant problem.

T – Okay, I want to get back to that point where you picked the calcium over the sulfur. Can you think of another approach that you could have taken?
J – To solving the problem?
T – Yeah.
J – Well, I was thinking that because no substances are supposed to be destroyed or created in a reaction. that if you just took the calcium and the sulfur and added them together that you should get the answer, but I wasn't sure if that was correct or not. So I went back to taking the grams needed to the ···· or grams given to get the moles given to the moles needed to the moles needed or the grams needed.
T – Okay.
J – 'Cause I was pretty sure that one was correct.
T – Okay, but again why would you pick calcium over sulfur? How would you ···· how would you make that decision?
J – I don't know... basically I just used that one because it was listed first, I think.
T – Okay.
J – And because it was like an even 50 instead of the 32 grams.

Jaymin seemed to struggle with not knowing which one to use between the calcium and the sulfur. Jaymin was asked to try another approach starting with the sulfur. She employed the factor-label algorithm, starting with sulfur, and recognized that the answer for the mass of calcium sulfide using this approach was not the same as when she had started with the calcium. Still unable to explain this, she was asked to consider just the first step in applying the factor-label algorithm. In this step, the number of moles of the starting substance was calculated. When the factor-label algorithm was used, this number of moles was never separately written down, because the calculation was only carried out after all conversions (grams --> moles --> moles --> grams) had been written down. The student then did the calculation all at once on a calculator, multiplying numerators and dividing by denominators, to obtain one final answer. There was a definite disadvantage to using the factor-label algorithm in this manner because the student could not see and evaluate interim results. When Jaymin calculated the number of moles for each substance, stopping after the first step of the factor-label algorithm, she finally recognized that 1.25 moles of calcium was in excess of the 1.00 moles which was calculated for the sulfur.

Jamin's major flaw was the assumption that the value for calcium should be used initially in the limiting reactant problem because it was listed first, and it was an easier number to work with. Rather than labeling this a misconception, it might be a sort of "I don't know how to do this, so I'll try this" effort to come up with an answer to the problem. She seemed to be very unsure of her answer after making this assumption, and knew that there must be a better way to determine the solution to the problem. The following excerpt from the Jaymin's transcript backs up these conclusions.

J – Okay. You've got 50.0 grams of the calcium and 32.0 grams of the sulfur. *(very font pause)* And you need to take the 50.0 grams of calcium and then multiply that times one mole of calcium over 40.08 grams of calcium because that's the atomic weight of the ···· And then multiply that times one mole of CaS over one mole of calcium. And then multiply that times the atomic weight of the calcium sulfide. It'd be 40.08 plus sulfur is 32.07 which comes to a total of 72.15 grams over one mole of calcium sulfide. And then I take 50 divided by 40.08 times 72.15 and I get a total of 90.01grams of the calcium sulfide for an answer. *(pause)* Okay?

T – Okay, one thing I would like you to consider in this problem is that there is also another number given – a 32 grams for the sulfur. Does that have anything to do with figuring out how much calcium sulfide would be produced?

J – I'm not sure 'cause I think there's like another equation I could have used that's short, or but I can't remember that one. So····

T – Okay.

J – I'm not sure if you just take the two and add'em. If you get an answer. I wasn't sure if that one was right.

T – Okay. Why did you choose calcium?

J – Umm...Umm... I'm not sure. I just decided to use that one.

T – Okay.

J – Or wait, hang on a second. I think I found something that was wrong. Oh... Okay, I'm wrong. I was thinking that was set up wrong because the calcium that I started with was 50.0 grams.

T – Okay. So you're not really sure why you chose calcium instead of sulfur?

J – No, just 'cause it was the first one.

T – Okay.

J – It would probably be easier to multiply times 50 than by 32.

In summary, Jaymin's ability to recall information that had been learned/practiced/quizzed in class greatly assisted her problem solving. She was able to demonstrate conceptual understanding of the mole concept and use appropriate labels throughout her work. Miwon, however, was not able to recall the appropriate use and definition of the mole concept. It is apparently true that it never became a part of her repertoire of knowledge and skills during the time it was learned/practiced/quizzed in class. Being able to more easily recall and repeat definitions, labels, and concepts that have been discussed and studied in class gives Jaymin an advantage when asked to tackle similar problems down the road. Therefore, Jaymin did demonstrate conceptual understandings which were closer to the accepted scientific view. These conceptual understandings were largely the result of her being able to recall information and methods that were learned during the stoichiometry unit, as it was covered in class.

Table 3. General strategies / heuristics

Miwon	Jaymin
Problem 1 - Stoichiometry	**Problem 1 - Stoichiometry**
Trial and Error Findings the gram-formula mass for hydrogen and nitrogen but can't figure out how to use it **Hill Climbing** Finds the gram-formula mass for two of the substances in the balanced equation: NH_3 and N_2	- Checks interim results against Information held in memory: Realizes that 14.01 and 1.01 are incorrect formula masses N_2 and H_2
Means-Ends Analysis Searches for H_2 value; determines the H_2 value by subtracting N_2 from NH_3 - Breaks Problem into Parts: Expresses a numerical value for each step she takes **Verifies Answer** Computes the same result by finding the mass for 3 moles of H_2, thus finding the same answer using two different calculations	**Means-Ends Analysis** Recognizes the result needed, employs steps (factor-label algorithm) to get there. She uses the factor-label algorithm for the stated problem, and when asked to find the grams of NH_3 produced, also describes how it would be used
Problem 2 - Fruit salad	**Problem 2 - Fruit Salad**
- Breaks problem into parts: For example, to find oranges needed, she first finds the total apples bought, divides by the number needed for 2 batches, and then multiplies by the number of oranges needed for 2 batches	- Breaks problem into parts: For example, to find the money saved, she first finds the total cost when the apples are not on sale, and then finds the total cost when the apples are on sale; she then subtracts to find the money saved **Verifies answer/rereads question** Realizes 5 oranges plus 8 apples makes 2 batches, not 1 batch, after rereading the question. Self-corrects this with no prompting
Means-Ends Analysis: Performs steps during each question of this problem which bring her closer to the correct solution	**Means-Ends Analysis** Performs steps during each part of this problem, which bring her closer to the correct solution
Problem 3 - Limiting reactant	**Problem 3 - Limiting reactant**
Menas-Ends Analysis Recognizes the result needed, employs steps (factor-label algorithm) to get there (incorrectly selects calcium to start with; uses the same approach with the sulfur and then calcium at 40.08 grams after questioning by the interviewer)	**Means-Ends Analysis** Determines a 1 mole to 1 mole to 1 mole relationship; finds the grams/mole for calcium sulfide but doesn't realize this is the correct answer
Trial and Error Tries calcium as the 'one to start with' over sulfur using the factor-label method; feels that answer may be "okay" **Verifies Answer** Recalculates twice using a	**Trial and Error** with record keeping: keeps track of the difference between the g/mole for calcium sulfide, and the mass found when simply adding calcium's given mass to

Table 3. (continued) General strategies / heuristics

Miwon	Jaymin
calculator to make sure the calculations are done correctly **Rereads the problem** To make sure it is the calcium sulfide that is being sought **Hill climbing** Seeks answer starting with 40.08grams of calcium thinking it may lead to insight or nearer to the correct solution. Upon comparison, finds two numbers to add together to give a total of 10.08 grams of excess calcium	sulfur's given mass; attempts to find a relationship **Rereads the problem** In an effort to spur new thinking; checks to see if something was overlooked on the first read through the problem

Ⅳ. Conclusions and Implications

The problem solving approaches of two students were examined: the similarities and the differences in their problem solving approaches, and the general problem solving strategies (heuristics) the students employed were discussed. There are more similarities in the students' problem solving strategies than there are differences. Both students were able to correctly solve the stoichiometry and the fruit salad problems, and were unable to correctly solve the limiting reactant problem. They recognized that an algorithm could be used for both chemistry problems. Both students were unable to correctly solve the limiting reactant problem and to demonstrate a clear understanding of the Law of Conservation of Mass. Nor did they show an ability to apply it in solving the problem.

However, Jaymin had greater ability to extend what had been learned/practiced/quizzed in class to a related but different problem situation than Miwon. Jaymin also immediately recalled the algorithm, and used it to correctly determine the answer to the stoichiometry problem. Jaymin demonstrated a conceptual understanding which is closer to the accepted scientific view than Miwon did.

This information can help science educators in a number of ways. First, teaching should involve more than just demonstrating to students how to apply an algorithm. An understanding of the science concepts related to the problem is essential prior to the application of an algorithm. An understanding of what an algorithm is and why it works is also important. Different approaches to solving the same problem should be demonstrated and practiced as well.

Second, students should be challenged with problems which are related to, but different from, the basic problems under study. Teachers should present problem situations to students in which they have to deal with extraneous data, modify an existing algorithm, or develop their own algorithm(s).

Third, in spite of the most carefully planned instruction, alternative conceptual ideas continue to persist in the minds of students. For teaching, we should make serious efforts to solicit from students what their ideas are regarding a particular concept, design instructional activities which challenge these ideas, present them with anomalous situations, and allow them to discuss/debate their ideas with other students.

References

Ambruso, M. D. (2003). Challenging students with experiments. *Science Teacher*, 70(1), 41-43.

Asirvatham, M. (2004). *Enriching science through diversity*. from http://www.colorado.edu/ftep/diversity/div12.html

Carson-Dellosa Publishing (1994). Thematic units collection. Carson-Dellosa Publishing co, Inc. NC: Greensboro.

Gendell, J. (1987). The solution is not the problem. *Journal of Chemical Education*, 64(6), 523-524.

Good, R. & Smith, M. (1987). How do we make students better problem solvers?. *Science Teacher*, 54(4), 31-36.

Herron, J. D. (1975). Piaget for chemists - explaining what "good" students cannot understand. *Journal of Chemical Education*, 52(3), 146-150.

Kean, E., Middlecamp, C. H., & Scoot, D. L. (1988). Teaching students to use algorithms for solving generic and harder problems in general chemistry. *Journal of Chemical Education*, 65(11), 987-990.

Kim, Sung-Geun, Yeo, Sang-Ihn, & Woo, Kyu-Whan (1999). A study on students' questioning activity in science class. *JKARE*, 19(4), 560-569.

Lee, K. S. (1982). Fourth grader's heuristic problem solving behavior. *Journal for Research in Math Education*, 13(2), 110-123.

McCalla, J. (2003). Problem solving with pathways. *Journal of Chemical Education*, 80(1), 92-98.

National Science Teachers Association (1985). Science-Technology-Society: Science education for the 1980's, in *NSTA HANDBOOK 1985-86*. Washington, DC: National Science Teachers Association.

Problem solving techniques and algorithms (2004). from www.heliosat3.de/e-learning.

Rief, F. & Larkin, J. H. (1991). Cognition in scientific and everyday domains. *Journal of Research in Science Teaching*. 28(9), 733-760.

Tobias, S. (1990) *"They're not dumb, They're different: Stalking the second tier."* Research Corporation, Tucson, Arizona.

Wilson, E. O. (1992). *The diversity of life*. Belknap Press of Harvard University Press.

APPENDIX

Problem 1

The balanced chemical equation for the synthesis of ammonia is:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

How many grams of hydrogen would be needed to completely react with 28.0 grams of nitrogen?

Problem 2

Youmin invites her friends home to have a birthday party. One of the food items Youmin's mother often makes is a fruit salad.

The recipe she uses for fruit salad calls for 5 oranges and 8 apples. This makes 2 batches of fruit salad.

Youmin's mother purchased by the dozen. Oranges normally cost 2500won for a dozen, while apples normally cost 2000won for a dozen. That day a special is listed at 1500won for one dozen apples. She takes advantage of the deal and buys 6 dozen apples.

Not wanting to waste any of apples, Youmin's mother decides to also buy enough oranges (by the dozen) so that the fruit salad recipe can be followed.

Explain and show how Youmin's mother can figure out the following.

1. How many oranges does she need in order to follow the recipe and use all 6 dozen apples?
2. How many oranges will she have to buy at the store?
3. What is the total cost of purchasing apples and oranges for the fruit salad?
4. How much money does she save by purchasing the 6dozen apples when they are on sale?
5. How many batches of the fruit salad can be made?

Problem 3

The balanced chemical equation for the synthesis of calcium sulfide is:

$$Ca(s) + S(s) \rightarrow CaS(s)$$

Suppose that 50.0 grams of calcium and 32.0 grams of sulfur are reacted to form calcium sulfide. How many grams of calcium sulfide will be formed as a result of the reaction?