The High School Chemistry Laboratory Can Strengthen Abstract Reasoning Skills

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As the prelude I begin with a quotation that capsulates the impact that this study may have for science education at the secondary school level.

> "Andrea, who showed only concrete reasoning ability at the beginning, blossomed as the experiments progressed. One could actually witness her improved thought processes. She seemed to develop better lab technique over the course of the two and one-half months, and with each new experiment she approached it in a more scientific manner."

So wrote Lucy Brooks, chemistry teacher at West Central Boone Junior-Senior High School, who collaborated with me in this project.

The rationale underlying this study is the truism that abstract reasoning abilities are essential for the mastery of all academic disciplines. Yet, little formal attention is given to encourage the cognitive development of the high school student. As teachers we stress course content and pay little or no attention to how the student thinks. In Piagetian terminology we science teachers discuss many concepts that demand formal operational thought to students of only concrete operational ability. Herron (2) argues that as many as 50% of the entering college freshman operate entirely at the concrete operational level. McKinnon and Renner (4) on the basis of administering five Piagetian tasks to 131 college freshman at the University of Oklahoma found that 50% of the students were only concrete operational. Renner and Lawson (6) administered two tasks, one requiring the comprehension of volume conservation and the other variable exclusion, to high school students in the Norman, Oklahoma school system. Of the 196 high school juniors and seniors tested 51% were unable to apply the concept of conservation of volume correctly on the one task and 63% were unable to identify the correct variables on the variable exclusion task. If 50% of the entering college freshman only operate cognitively at the concrete operational level, is it any wonder that many find the first semester of college an academic disaster?

One of the authors was introduced to the use of Piagetian Puzzles at a workshop on "How People Think?" which was directed by R. Fuller and M. Thornton from the University of Nebraska-Lincoln (1). He has used one, The Frog Puzzle, which was developed at the University of California, to assess the capabilities of certain college classes to use proportional reasoning for the past three years. The essence of the Frog Puzzle follows; the results are summarized in Table 1.

The Frog Puzzle

An ecologists conducted an experiment to determine the number of frogs that live in a particular pond. Since he was unable to catch all of the frogs, he caught as many as possible, banded them, and released them back into the pond. A week later he returned to the pond and again he caught as many as he could. Here is his data.

TABLE 1. *Student Performance on the Frog Puzzle*

Class	Number	No Idea Percentage	Concrete Percentage	Transitional Percentage	Formal Percentage
Introductory Chemistry	112	4	38	21	37
Educational Psychology	32	0	63	12	25
Introduction To Quantitative Reasoning	159	14	72	5	9
Total	303	8	59	12	21
High School Chemistry Class	12	0	67	8	25

First Trip to the Pond

55 frogs caught and banded

Second Trip to the Pond

72 frogs caught, of these 72, 12 were banded.

In the week interval the ecologist assumed that the banded frogs had mixed thoroughly with the unbanded frogs. From this data he was able to approximate the number of frogs in the pond. If you can compute this number, do so. In the blank space below your answer, clearly explain how you calculated your result.

Total Number of Frogs in the Pond

In general the student responses fall into one of the following categories:

1. I have no idea.
2. On the first trip 55 frogs were banded, and on the second trip 12 of the 72 frogs were banded leaving 60 new unbanded frogs. Consequently, the total number of frogs is 60 + 55 = 115. (Concrete Reasoning)
3. Twelve of the 72 or one-sixth of the frogs are banded. Therefore, 55 = 1; N equals 330 frogs in the pond. (Formal Reasoning)
4. Of the 72 frogs 72 - 12 or 60 were not banded; consequently, 12/60 or one-fifth of the frogs in the pond are unbanded. Depending on the interpretation of the student, an answer of 275, 300, or 360 frogs is given. (Transitional Reasoning)

Of the 303 DePauw University students who were tested using the Frog Puzzle, only one-third of them utilized proportional reasoning. The chemistry class of 12 students at West Central Boone Junior-Senior High School were given the same Frog Puzzle. Their performance parallels that of the combined college group. This strongly indicates that cognitively the college-bound high school junior or senior student differs little from the average college freshman student.

The Learning Cycle described by Karplus (3) which was developed as part of the Science Curriculum Improvement Study (1970-1974) is a pedagogical technique that is specifically designed to encourage the introduction of formal concepts. The Learning

Cycle has the goal of strenghtening the reasoning ability of the student. Each Learning Cycle consists of three separate tasks and relies heavily on peer group interaction. Students learn from students rather than learning from the instructor who is present to guide inquiry rather than provide answers. The three phases are:

(1) Exploration which involves empirical observations of selected phenomena using the materials that are provided.

(2) Invention which develops laboratory technique, introduces quantitative calculations, and may demand the design of an experiment.

(3) Application which involves solving a problem using the ideas that are generated in the Exploration and Invention activities. In certain instances the Application activity may be an out of class exercise that demands formal reasoning patterns of the students.

The structure of the Learning Cycle makes it adaptable for use in a one-hour laboratory period format. Instead of doing Exploration, Invention, and Application as a three-hour exercise, they are done as three, one-hour exercises. During a National Science Foundation Faculty Development Fellowship at the University of Nebraska-Lincoln, one of the authors developed a set of Learning Cycles for use in the introductory college chemistry laboratory.

The realization that the average college freshman and the college-bound high school junior differ very little in their reasoning abilities prompted this study to see if the Learning Cycles experiments might be effective in encouraging the cognitive development in the high school student. Lucy Brooks tested this premise with her class of twelve chemistry students at West Central Boone High School. The class did the four Learning Cycles which are described below. The number in parentheses gives the number of single laboratory periods that are required to complete the experiment.

A CHEMICAL DILEMMA (2) stresses combinatorial reasoning which requires the student to analytically consider all possibilities and correlational reasoning which requires the student to interpret cause and effect relationships. Chemically the experiment involves an empirical study of precipitation reactions from which the student can identify certain aqueous solutions.

INDUCTIVE REASONING FROM CHEMICAL EXPERIMENT (4) demands both combinatorial and correlational reasoning as well as propositional reasoning which requires the student to identify variables and test certain hypotheses experimentally. A study of precipitation and filtration techniques permit the student to design and test his own scheme of qualitative analysis for any mixture of the cations, Hg_2^{+2}, Ag^+ Ba^{+2}, Al^{+3}, and Cd^{+2} using dilute solutions of HCl, H_2SO_4, HNO_3, $NaOH$, and aqueous NH_3.

THE PLOT THICKENS (5) emphasizes the construction and interpretation of a graph, the use of proportional reasoning which requires the understanding of the quantitative relationship between variables, and propositional reasoning. Using fractional crystallization techniques the student is asked to separate a mixture of sodium chloride and potassium dichromate.

THE GREAT TITRATION MYSTERY (10) demands correlational, proportional, and propositional reasoning. This experiment introduces titration techniques plus the concept of molarity and its use in chemical calculations. Students empirically investigate the behavior of strong and weak acids when titrated with strong base in the presence of various indicators. This is followed by standardizing a solution of sodium hydroxide which is then used to titrate an equimolar mixture containing two of the following

TABLE 2. *Cost of Experiments for 60 Students*

Chemicals	Learning Cycle	Description
\$36.44	The Chemical Dilemma	Cost based on 500 ml. of 0.5 molar $BaCl_2$, $Pb(NO_3)_2$, $AgNO_3$, Na_2SO_4, and NaI.
\$17.71	Inductive Reasoning	Cost based on 500 ml. of solutions, $Hg_2(NO_3)_2$, $Al(NO_3)_3$, $AgNO_3$, $Ba(NO_3)_2$, and $Cd(NO_3)_2$, containing 25 mg./ml. of the cation and 1 liter each of the dilute acids and bases.
\$ 6.70	The Plot Thickens	Cost based upon the use of 1 lb. each of NaCl and $K_2Cr_2O_7$.
\$ 2.95	The Great Titration Mystery	Cost based upon 500 ml. of 0.1 molar HCl, $HC_2H_3O_2$, H_3PO_4, and 2 liters of each of the acid mixtures which are 0.05 molar with respect to the acid. Included in the cost are the indicator solutions, potassium acid phthalate, and the NaOH solutions used in the titrations.

Equipment	Description
\$225.00	30 Plastic Bottle Trays and bottles (30 ml.) with droppers.
\$ 25.50	Pasteur pipets (1000) as substitutes for burets.
\$ 10.00	Rubber bulbs for the Pasteur dropping pipets (50)
\$ 22.00	18 Polyethylene wash bottles (125 ml.)
\$500.00	18 Burets separable (50 ml.)
\$ 31.80	6 Pipets (25 ml.)

three acids, acetic, hydrochloric, or phosphoric. The student is asked to deduce which pair of acids is in the mixture and the respective molarities of each.

These Learning Cycles can be done quite inexpensively. For a class of sixty students the cost is \$63.81 for chemicals and \$282 for the initial investment in equipment if Pasteur pipets are used in place of volumetric burets and pipets. Table 2 summarizes the equipment and chemical costs. Copies of the experiments are available upon request from the author.

The class was pre-tested and post-tested using five, pencil and paper puzzles which assess the cognitive development of the students. Pre-testing was done with The Frog Puzzle, which measures proportional reasoning ability, and The Islands Puzzle, which measures both propositional and combinatorial reasoning ability. The post-testing was done using The Ratio Puzzle, which assesses proportional reasoning ability, The Algae Puzzle, which measures combinatorial reasoning ability, and The Mealworm Puzzle, which requires both propositional and correlational skills. The student performances on these tests appear in Table 3. Copies of these puzzles will be supplied on request.

The small sample size and the absence of a control group preclude making any firm conclusions as to the effect of the Learning Cycles on cognitive ability. However, one does see that 1) those students who pre-tested formal operational remained formal operational, 2) no student's cognitive abilities decreased even though two of the group remained at the concrete operational level, and 3) seven of the group demonstrated significant improvement in their cognitive skills. Smith (7) describes a high school chemistry course that is designed to encourage cognitive development and reports that those students who participated in the course outperformed those students taking a traditional course on a test that required propositional logic, proportionality problems, and combinatorial analysis. Whisnant (8) uses twenty-five Learning Cycles in his college general chemistry course, however, he is uncertain as to whether they help the students develop cognitively. The one theme that appears in the articles involving the use of the Learning Cycle in the laboratory is that both the students and the instructors seem to enjoy this approach.

TABLE 3. *High School Student Performance on Piagetian Puzzles*

Student	Class	Pre-test Frog	Island	Ratio	Post-test Algae	Mealworm
1.	Jr.	C	C	F	F	C
2.	Sr.	Tr.	Tr.	F	C	C
3.	Jr.	C	Tr.	F	Tr.	F
4.	Sr.	N.E.	C	C	Tr.	C
5.	Sr.	C	Tr.	C	Tr.	C
6.	Sr.	N.E.	F	F	F	Tr.
7.	Jr.	F	F	F	F	Tr.
8.	Jr.	C	C	F	F	C
9.	Jr.	C	C	F	F	C
10.	Sr.	C	C	C	Tr.	Tr.
11.	Jr.	F	C	F	F	Tr.
12.	Jr.	F	C	F	F	Tr.

C - Concrete Operational Tr. - Transitional between Concrete and Formal Operational F - Formal Operational
N.E. - No evaluation possible.

As teachers of science we can use the laboratory to teach science skills and reasoning skills. To accomplish this, simply rewrite the experiments in a manner that will force the students to devise the procedure to test certain hypotheses and answer posed questions. Pickering (5) puts it this way,

"Confrontation with the unknown is good experience for all students regardless of their reasoning abilities."

My final admonition is to determine the reasoning abilities of your class. With the knowledge of their cognitive capabilities you will become a more effective teacher and they will become more effective learners.

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