Developing Critical Thinking Skills Through the Use of Guided Laboratory Activities

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Abstract

In a study to evaluate an approach for improving the critical thinking skills of middle school science students, 60 students were given the assignment of completing three guided laboratory activities and writing a report for each. In writing their reports, students were expected to identify the manipulated variable, identify the responding variable, write a statement of the problem, make a prediction, display the data in a well-organized table, depict the data from the table in a graph, and write a conclusion that showed how the data supported or refuted the prediction. Higher level thinking skills demonstrated by such tasks included analysis, synthesis, and evaluation. The student laboratory reports were evaluated using a comprehensive rubric. It was found that repeated use of the guided laboratory activities produced remarkable improvements in students' higher-level thinking skills.

Introduction

As an undergraduate student in biology during the 1960's, I recall one of my professors remarking to our class prior to our final examination that "an education is what you have left after you forget everything you learned in school." I consider that statement quite prophetic. Gone are the days when memorization and recitation of facts represented the major focus of the science and mathematics disciplines. No longer will "the notes of the professor travel to the notes of the student without going through the minds of either" (author unknown, but a statement that has been used in numerous workshops and conferences during the early 1990's.) Through years of deliberate change emanating from within our ranks, and out of a common distaste for our experiences as students, we educators are beginning to thrive in an era that will be characterized by our commitment to developing critical thinking skills in our students.

For a number of years now, one of the first observations I have made of my entering students has been a general lack of facility with application, analysis, synthesis, and evaluation. Such abilities comprise the upper four levels of Bloom's Taxonomy (Bloom, 1956). For example, when my students were given a hypothetical problem in which they had to make a prediction and design an experiment to test that prediction, only one third of them were successful at both tasks.

I believe the lack of ability to use critical thinking skills is a result of not having enough experience using those skills. Consequently, I think students can improve their critical thinking skills if they are provided with more opportunities to use such skills. This research focused on whether the use of frequent guided activities can provide such opportunities and result in the improvement of critical thinking skills.

Review of Literature

A survey of science teachers determined that the “most common objective listed by faculty members for the laboratory component is simply to reinforce lecture material” (Sundberg, Armstrong, Dini, & Wischusen, 2000, p. 353). While that might have been the experience for many of us who received the bulk of our formal science education during the 1960’s, such an assertion appears to run contrary to the very essence of how science was developed as a body of knowledge. It still seems to be forgotten, or perhaps never learned, by many that the entire field of science as we know it was developed as a result of open-ended, inquiry-oriented investigations by independent-thinking individuals. It seems reasonable, therefore, that science labs, rather than being used primarily as a reinforcement of rote lecture material, should also provide students with opportunities for both the discovery of declarative knowledge and practice using critical thinking skills.

While we are purposefully made cognizant of the importance of developing critical thinking skills in students at the middle school level, it is significant that this trend does not necessarily lose its momentum when students take science classes in college. It has been argued by some of my colleagues, past and present, that teaching critical thinking skills might prove to be ineffective, given that experiences in college science classes showed a large portion of what was taught was content-oriented, rather than process-oriented. However, to the enlightenment of many, some college teachers are showing a commitment to a major goal of educational reform that there needs to be a transition from “the method of teaching facts to emphasizing higher-order cognitive skills learning” (Zoller, 2000, p. 409). Higher-order cognitive skills learning is essentially on the same cognitive level as critical thinking skills. In addition to critical thinking, examples include “question asking … decision making, problem solving, and evaluative thinking” (Zoller, 2000, pp. 409-410). Therein described are some of the same higher-order thinking skills that are a requisite component of the scientific process used in problem-solving at the middle school level.

It is noteworthy that the development of critical thinking skills through the use of inquiry laboratory activities does not necessarily limit the critical thinking skills to the learning of science. A more global goal for developing critical thinking skills is to enable students to “participate effectively in the decision-making, problem-solving process of our democratic society” (Zoller, 2000, p. 409).

Based upon workshops I have attended, conversations with colleagues in other academic disciplines, and pedagogies written in current curriculum guides, it appears that there is considerable consensus among educators that the importance of developing critical thinking skills can supersede the importance of merely acquiring knowledge, and that in order to develop critical thinking skills, students need to have experience with activities that are intended to develop them. “Students cannot learn to think critically, analyze information, communicate scientific ideas, make logical arguments, work as part of a team, and acquire other desirable skills unless they are permitted and encouraged to do those things over and over in many contexts” (Eyster, 1997, p. 19).

An example of an approach that focuses upon developing critical thinking skills by exposure to activities emphasizing such skills was demonstrated by Kronberg and Griffin (2000) in their use of analysis problems. “This technique requires students to move beyond comprehension to the levels of application, analysis, and synthesis” (Kronberg & Griffin, 2000, p. 349). They used multiplechoice questions in which the students were presented with a hypothetical situation and had to choose the response that best answered the problem, also justifying not only their selection of the best choice, but also their rejection of all other choices. The work was evaluated not so much upon the accuracy of their answers, but rather upon the "adequate justification for his or her response" (Kronberg & Griffin, 2000, p. 351).

The authors pointed out that while, as the semester progressed, most students found the approach initially challenging but enjoyable, those students used to recall level questions found the experience to be frustrating (Kronberg & Griffin, 2000, p. 351). I have had similar experiences using open-ended activities in my classes. Many students who have shown considerable past success based upon their acute ability to memorize sometimes similarly found the transition to higher-level thinking a frustrating experience.

Methodology and Research Design

Over the years, I have developed several guided laboratory activities, and when I evaluated them through the lens of Bloom's Taxonomy (Bloom, 1956), I found they were a virtual gold mine of critical thinking skills. That is, when the laboratory report format for each laboratory was broken down into a series of tasks, it was clear that each task required the use of specific critical thinking skills that make up the upper levels of Bloom's Taxonomy. Table 1 provides the format that my students are asked to follow as they write a formal laboratory report, as well as the corresponding critical skill demonstrated by each task.

The students selected for this study were enrolled at Venado Middle School, Irvine, California, where I have worked as a science teacher for 28 years. I teach six 7th-grade general science classes. All classes have students with a range of abilities. Most are average middle school students. Some students are enrolled in special education, and others are classified as gifted. Their cognitive abilities were not a factor in selecting the students to be the subjects of the study. The 60 students I chose were selected using a random numbers table.

To triangulate the data, three data collection techniques were used: informal interviews, classroom observations (clipboard notes), and the examination of student work products using a rubric. Prior to performing the first lab and writing the subsequent laboratory report, the students were given a hand-out on how to do a science project, and I proceeded to use a PowerPoint presentation that explained how to use a scientific problem-solving approach to perform their science projects. During the first laboratory assignment, Heat Loss (Appendix A), the students were provided the laboratory assignment sheet shown in the appendix. Included in this was the procedure for performing the lab and the seven-step format to be followed in writing the laboratory report. These steps are represented by the elements of column 1 in Table 1. I actively taught both the experimental procedure and the format for writing the laboratory report.

The students worked in groups of 4, a necessity when class sizes are as high as 36. While they were engaged in the lab, which included writing the report, I randomly approached students who belonged to the selected sample and talked with them informally about the activity. Depending on the part of the lab on which they were working, I asked them questions selected from those shown in Table 5. For example, if I noted a group were involved in data collection, I might have asked them about what they believed to be the investigative question, or statement of the problem. Given the constraints imposed by both time and the other duties to which I also needed to attend during the laboratory activity, I chose to interview just 20 students during the lab.

Table 1
Laboratory Report Tasks and Accompanying Critical Thinking Skills

Laboratory report task	Critical thinking skill demonstrated
Identify the manipulated variable.	**Evaluation**. Making choices based upon reasoned arguments. (Select, judge)
Identify the responding variable.	**Evaluation.** Making choices based upon reasoned arguments. (Select, judge)
Write a statement of the problem in the form of a question that asks how changing the manipulated variable affects the responding variable.	**Synthesis.** Generalizing from given facts. Relate knowledge from several areas. (Compose, combine, create)
Write a prediction of how changing the manipulated variable would affect the responding variable.	**Synthesis.** (Predict, relate knowledge from several areas)
Collect and organize the data in a table that is logical and understandable.	**Analysis.** Organization of parts. Identification of components. (Order, classify, arrange)
Design and draw a graph that clearly depicts the data from the data table.	**Synthesis.** Relate knowledge from several sources. (Plan, create, design)
Write a conclusion that explains how the data and graph supports or refutes the prediction.	**Evaluation.** Verify value of evidence. Make choices based upon reasoned argument. (Assess, select, judge, summarize, compare)

While students were working on the activity, I moved around the room, making myself available for questions. If a student was having difficulty with some part of the experimental work or the report, they either made eye contact with me or raised their hand to indicate they needed assistance. Observations were made about anything I considered significant, and included the questions students asked, which I categorised. However, only the observations pertaining to those students I had also interviewed were retained.

The laboratory reports were graded according to the rubric of Table 2. The reports, together with the rubrics showing how each report was evaluated, were then returned to students.

Table 2
Laboratory Report Evaluation Rubric

Excellent (3)	Good (2)	Needs improvement (1)
Manipulated variable clearly identified.	Manipulated variable identified, but there may be an element of vagueness.	Manipulated variable not properly identified.
Responding variable clearly identified.	Responding variable identified, but there may be an element of vagueness.	Responding variable not properly identified.
The problem is clearly stated as a question and clearly indicates a direct, causal relationship between the manipulated variable and the responding variable.	The problem is stated as a question and shows a causal relationship between the student's understanding of the manipulated variable and the responding variable.	The problem was either not stated at all or it was stated in a manner that shows little or no relationship between the manipulated variable and the responding variable.
The prediction clearly explains how changing the manipulated variable will affect the responding variable.	The prediction shows a relationship between the manipulated variable and the responding variable.	The prediction was either lacking or it showed no relationship between the manipulated variable and the responding variable.
The data has been collected and organized into a data table that clearly and logically displays the data in a readily understandable fashion.	The data is collected in a table, but the table can be organized in a more easily understandable fashion.	The data is collected, but shows little organization and consequently is not presented in an understandable fashion.
A graph has been drawn that clearly depicts the data from the data table. It is readily understandable. It has a descriptive title, the vertical and horizontal axes are identified, and the units are properly labeled.	A graph has been drawn that depicts the data from the data table and is readable, but it could be more easily understood using another format. It has a descriptive title, but there may be some improvements, such as identifying the axes and the labeling of proper units.	A graph was either not drawn, or it was drawn such that the descriptive title is lacking; the axes are not straight; the units are not properly labeled; the intervals on the axes are not evenly spaced.
The conclusion clearly shows not only whether the laboratory data supports or refutes the prediction, but explains why or how.	The conclusion indicates whether the prediction is correct, but it is not clearly shown how the data supports or refutes the prediction.	The conclusion bears little or no relationship to the prediction. It is not shown how the evidence supports the conclusion.

Two further guided laboratory activities (Appendices B and C) were performed, thus giving three such activities over a period of 2 weeks. For the purpose of conducting a properly controlled study, I provided the same instructional treatment for these two activities, Rate of Heat Loss and Mass and Velocity. The students were given immediate feedback by receiving their graded laboratory reports and the accompanying rubric that defined what was expected. Prior to performing each succeeding laboratory activity, I actively taught the concepts listed in the performance criteria of the rubric shown in Table 2. The students I interviewed and observed were not necessarily the same for each lab.

Results

Tables 3, 4, and 5 show the results of the study.

Data Interpretation

Table 3 indicates that, after the first lab, roughly one fourth of all students were able to complete a laboratory report showing the seven desired outcomes found on the left column of the evaluation rubric. After completing the second laboratory report, the improvements were remarkable. What was even more impressive, though, were the results after evaluating the reports from the third experiment. With the exception of writing the conclusion, roughly three fourths of all students were able to turn in a laboratory report achieving the desired outcomes. It seems that the experience of having completed two prior labs contributed significantly to my students' ability to engage in critical thinking skills as manifested by their achieving the desired outcome.

The oral interviews, in which I directed the questioning, corroborated the rubric results fairly closely. For example, the percentages of students who could verbally identify the two variables in the labs increased as dramatically as they did when the students showed the same ability in the completed laboratory reports.

While the percentages of students being able to write a conclusion increased significantly from the first lab to the second lab, there was no corresponding increase in the third lab. This is corroborated by the observational data and the results of the informal interviews. A trend that I have noticed in students over the decades I have taught is that a portion of a typical class curiously seems unwilling to expend significant effort to explain an answer. For example, many of the conclusions were commonly stated "the graph went down so I was right." There was no further explanation. On the more optimistic side, a significant number of students were willing to evaluate the data extensively enough to justify their conclusion as to whether or not their prediction was supported by the data. Their conclusions easily expanded to include a paragraph of explanations.

Table 3
Examination of Student Work Products Using the Rubric

Desired outcome	Cognitive domain	Percent (%) achieving outcome		
		First lab report (N=57)[a]	Second lab report (N=60)	Third lab report (N=60)
Manipulated variable clearly identified.	Evaluation	35	56	77
Responding variable clearly identified.	Evaluation	26	56	71
The problem is clearly stated as a question and clearly indicates a direct, causal relationship between the manipulated variable and the responding variable.	Synthesis	29	60	74
The prediction clearly shows how changing the manipulated variable will affect the responding variable.	Synthesis	26	62	78
The data has been collected and organized into a data table that clearly and logically displays the data in a readily understandable fashion.	Analysis	23	55	86
A graph has been drawn that clearly depicts the data from the data table. It is readily understandable. It has a descriptive title, the vertical and horizontal axes are identified, and the units are properly labeled.	Synthesis	21	48	62
The conclusion clearly shows not only whether the laboratory data supports or refutes the prediction, but it explains why or how the data supports or refutes the prediction.	Evaluation	21	53	54

[a] Three of the selected students were absent for this lab.

Table 4
Behaviors Observed in the Classroom

Behavior Observed	Number of occurrences		
	First lab	Second lab	Third lab
Asked teacher definition of manipulated variable.	7	4	4
Asked teacher definition of responding variable.	7	2	0
Asked teacher to identify manipulated variable.	7	7	6
Asked teacher to identify responding variable.	6	6	6
Asked teacher to recite statement of the problem.	10	5	4
Asked teacher to state a prediction.	7	5	4
Needed to be prodded to participate in lab (not recording data, off-task, etc.)	8	3	5
Asked difference between data table and a graph.	4	1	0
Did not follow laboratory procedural directions.	8	3	3

Table 5
Student Responses During Interviews (N=20 for each lab)

Question asked	Percent (%) responding correctly		
	During first lab	During second lab	During third lab
What is the manipulated variable?	20	50	80
What is the responding variable?	25	50	75
What is the statement of the problem?	20	55	70
What is your prediction about the outcome of the experiment?	25	60	80
How does the data support or refute your prediction?	15	50	50

Discussion

The question I sought to answer was whether the frequent use of guided laboratory activities would develop critical thinking skills. It has been shown that there was a dramatic increase in the percentages of students achieving the desired outcomes from the first to the second laboratory report. Similar improvements, although not as dramatic, were achieved on the third laboratory reports in all categories except forming an acceptable conclusion. At the start of the term, roughly one-fourth of my students demonstrated the ability to use critical thinking skills according to the criteria listed in my rubric. By the time they had completed the third activity, about three fourths of my students were able to use these critical thinking skills.

I infer from this study a concept that I am sure most educators have long known. Consistent exposure to activities that require the use and refinement of a particular skill is an effective means of accomplishing mastery of that skill. As is the case for other skills deemed worthy of being learned by our students, critical thinking skills can be learned by students if they are given ample opportunities to develop those skills.

References

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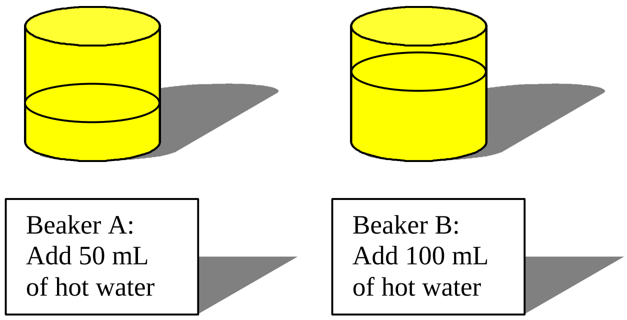
Appendix A

Lab: Heat Loss

Materials

- Two 100 mL beakers (labeled A and B)
- Thermometer
- Hot water



Procedure

1. Pour 50 mL of hot water into beaker A.
2. Pour 100 mL of hot water into beaker B.
3. Record, in a data table of your own design, the temperature of each beaker every minute for 10 minutes.

Write a formal **laboratory report**, using the following as a guide:

1) Identify the manipulated variable.
2) Identify the responding variable.
3) State the problem in the form of a question that uses the manipulated variable and the responding variable.
4) Write a prediction of how changing the manipulated variable would affect the responding variable.
5) Collect and organize the data in a table that is logical and understandable.
6) Design and draw a graph that clearly depicts the data in the data table. Be sure the graph has a descriptive title and appropriate keys, and that all units are properly labeled (e.g., mL, s, cm, and ^{0}C).
7) Analyze the data and graph. Write a conclusion that explains how the data and graph supports or refutes your prediction.

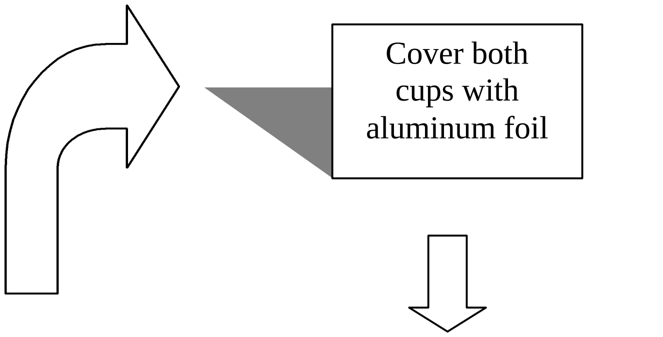
Appendix B

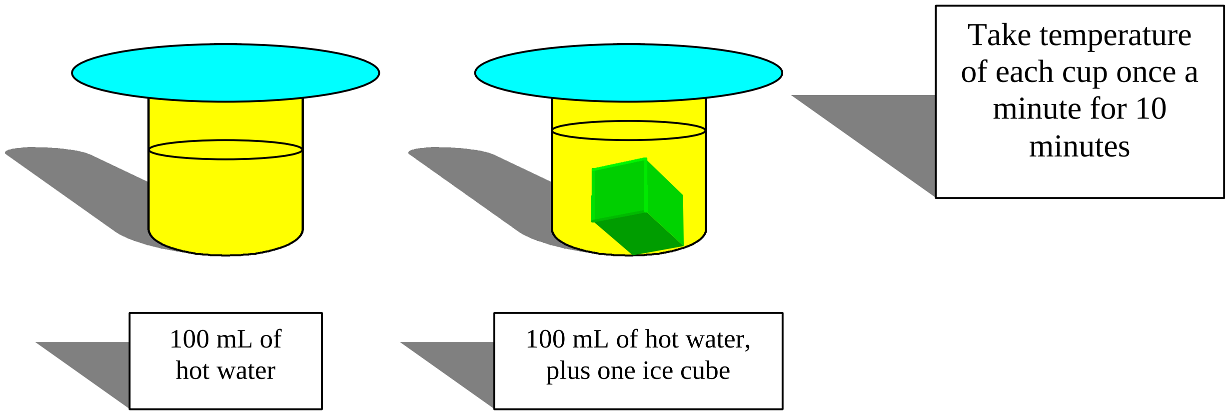
Lab: Rate of Heat Loss

Materials

- Two styrofoam cups
- 200 mL of hot water
- Two pieces of aluminium foil
- One ice cube
- Thermometer

Procedure





Write a formal **laboratory report** using the following as a guide:

1. Identify the manipulated variable.
2. Identify the responding variable.
3. State the problem in the form of a question that uses the manipulated variable and the responding variable.
4. Write a prediction of how changing the manipulated variable would affect the responding variable.
5. Collect and organize the data in a table that is logical and understandable.
6. Design and draw a graph that clearly depicts the data in the data table. Be sure the graph has a descriptive title and appropriate keys, and that all units are properly labeled (e.g., mL, s, cm, and ^{0}C).
7. Analyze the data and graph. Write a conclusion that explains how the data and graph supports or refutes your prediction.

Appendix C

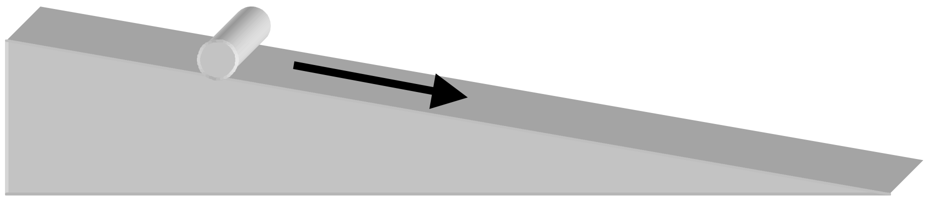
Lab: Mass and Velocity

Materials

Inclined plane
Meter stick
Watch with a second hand
Empty vial
Three marbles

Procedure

1. Set up the inclined plane so that one edge is lifted up 15 centimeters.
2. Record the time it takes for the empty vial to roll 100 centimeters down the inclined plane. Do this for a total of three trials, and enter the data in a table.
3. Put one marble in the vial and repeat step 2.
4. Put two marbles in the vial and repeat step 2.
5. Put three marbles in the vial and repeat step 2.



Write a formal **laboratory report** using the following as a guide:

1. Identify the manipulated variable.
2. Identify the responding variable.
3. State the problem in the form of a question that uses the manipulated variable and the responding variable.
4. Write a prediction of how changing the manipulated variable would affect the responding variable.
5. Collect and organize the data in a table that is logical and understandable.
6. Design and draw a graph that clearly depicts the data in the data table. Be sure the graph has a descriptive title and appropriate keys, and that all units are properly labeled (e.g., mL, s, cm, and ^{0}C).
7. Analyze the data and graph. Write a conclusion that explains how the data and graph supports or refutes your prediction.