Scientific Thinking and the Logic of Environmental Engineering Experiments

Dr. Veera Gnaneswar Gude P.E., Mississippi State University

Veera Gnaneswar Gude is a faculty member of civil and environmental engineering department at Mississippi State University. He has degrees in chemical (B.S.) and environmental engineering (M.S., Ph.D.) disciplines with over 10 years of academic, industrial, and research experiences on various chemical and environmental engineering projects. He is a licensed professional engineer and a board certified environmental engineer. His passion for teaching continues for over 10 years since his graduate school. He has been active with ASEE and educational research for over 10 years. He is particularly interested in enhancing critical thinking skills among civil engineering students through various educational approaches. His research interests include water and wastewater treatment, desalination, and algal biofuels.

©American Society for Engineering Education, 2016

Scientific Thinking and the Logic of Environmental Engineering Experiments

Abstract

Scientific thinking allows one to approach engineering problems by asking clear and well-thought-out questions. Because environmental engineering is based on applied scientific principles (knowledge from science, i.e. chemistry, mathematics and physics), scientific thinking can be very crucial in developing a deeper understanding of the subject matter. It seeks for *clarity*, *accuracy*, *precision*, *relevance*, *depth*, *breadth*, *logic*, *significance*, and *fairness* of the subject of interest. This paper discusses student responses in an Environmental Engineering Laboratory class, where they were given a set of questions formulated in "The Logic of Experiment" format to promote scientific thinking. This research activity is based on the hypothesis that scientific thinking exercises provide opportunities for students to improve their metacognitive abilities by asking clear questions about scientific/engineering problems that are otherwise not addressed in regular laboratory experiments or setups. These exercises also help students to apply core concepts of environmental science in a systematic manner to solve environmental engineering problems.

"The Logic of an Experiment" exercises were implemented in an undergraduate junior level environmental engineering laboratory course (CE 3801) in fall 2015. Students were asked to complete two scientific exercises (I and II) on a voluntary basis. These exercises were provided to students while they were working on actual laboratory experiments, to improve the quality of their learning experience and to increase the relevance of the subject to their experiments. In addition, another exercise (exercise III) was developed in form of a survey toward the end of the semester to evaluate students' understanding of scientific thinking in the nine critical areas listed earlier to evaluate their current knowledge on the topic. The summary of the student responses from scientific thinking exercises I and II and from the survey (exercise III) questions are discussed. Results from exercises I and II suggested that "logic of experiment" exercise along with guiding information in multiple attempts can help instill scientific thinking in environmental engineering students. Results from the survey suggested that by implementing "The Logic of an Experiment" exercise during laboratory sessions, the quality of student learning could be improved. It is also imperative that continuing this exercise beyond laboratory sessions will further enhance problem solving skills in students' professional lives.

Keywords

Laboratory instruction, scientific thinking, critical thinking, student performance, metacognition, experimental rigor.

"I am eligible for the Environmental Engineering Division Early Faculty Grant."

Introduction

Teaching and learning in an engineering course is a challenging task due to complexity of subjects and the required amount of comprehension, knowledge acquisition and application of the scientific principles learned from previous courses. Junior and senior level Civil Engineering students, especially, need to learn how to analyze a complex problem, evaluate alternatives and synthesize most efficient solutions. All these tasks are listed at the higher level of learning in Bloom's taxonomy in the cognitive domain[1]. They need to understand the importance of critical thinking as they prepare for real-world experience in their professional careers. Critical thinking involves reasoning, decision making, and problem solving while seeking for effectiveness, novelty, and self-direction[2]. Critical thinking is effective because it avoids common pitfalls, such as seeing only one side of an issue, discounting new evidence that disconfirms one's ideas, reasoning from passion rather than logic, and failing to support statements with evidence. There are many methods that can be implemented to encourage students to develop critical reasoning, decisive analysis and scientific judgement on any engineering problem.

In our previous efforts (see Figure 1), we introduced writing as an essential tool to instill critical thinking skills in junior and senior level Civil Engineering students. Other activities included supplemental instruction (SI), collaborative learning and project based learning of water and wastewater treatment and environmental engineering concepts[3-6]. Writing assignments provided a practical context that deepened student understanding and comprehension of the content area. Students developed written communication skills, a process for thinking through and solving civil and environmental engineering problems. Active learning in the classroom and self-directed learning outside of classroom created opportunities for students to apply knowledge and identify questions which were resolved in the SI session. Students followed a set of steps to develop proper questions and find their own solutions by applying critical thinking skills. Finally, project based learning, or projects that resemble real-world engineering problems created interactive and collaborative learning platforms in laboratory instruction and senior level design courses which in turn promoted the logical progression in creative thinking and thereby critical thinking.

Issues in laboratory course instruction

Laboratory courses are even more demanding of higher order thinking skills. They often involve exercises that require scientific thinking which is a combination of critical thinking, creative thinking and metacognitive thinking. Metacognitive thinking enhances critical thinking and fosters one's own scientific judgement while promoting self-regulation to result in a creative solution. Although many studies have been conducted to investigate educational effectiveness of laboratory course instruction in science and engineering disciplines and especially with the goal of promoting cognitive skills, the evidence of effectiveness of the laboratory courses is still sparse[7]. Many recent reviews have discussed this topic but these contributions have made it clear that research has failed to show simple relationships between experiences in the laboratory and student learning. Hodson[8] noted that laboratory work is unproductive, and confusing, because it is very often used without clear thought-out purpose, while Tobin[9] opined that laboratory activities appeal as a way to learn with understanding and, at the same time, engage in a process

of constructing knowledge by doing science. He also suggested that meaningful learning is possible in the laboratory if students are given opportunities to manipulate equipment and materials in order to be able to construct their knowledge of phenomena and related scientific concepts. However, there is hardly any evidence about the effectiveness of laboratory learning at the college level, either to show improved content understanding, or on science practices such as open-ended problem solving, or critical thinking[10]. Students are often not afforded the time necessary for the deep processing of information in laboratory sessions. It is through deep processing that students are able to integrate new experiences with prior knowledge, establish a context for the purpose of the laboratory activity, and determine the activity's relevance to themselves. All of which are characteristics of meaningful learning[12]. Secondly, in their current format, traditional laboratory activities are designed to facilitate the development of lower-order cognitive skills such as rote learning and algorithmic problem solving. Bloom's taxonomy of educational objectives is a hierarchical representation of six cognitive processes: knowledge (lowest), comprehension, application, analysis, synthesis, and evaluation (highest)[13]. This classification scheme is often dichotomized into lower and higher-order thinking processes. Behaviors that would exemplify the lower levels of cognition include remembering, recognizing, or applying a learned rule. Higher-order thinking is exemplified by such behaviors as inferring, planning, or appraising[11].

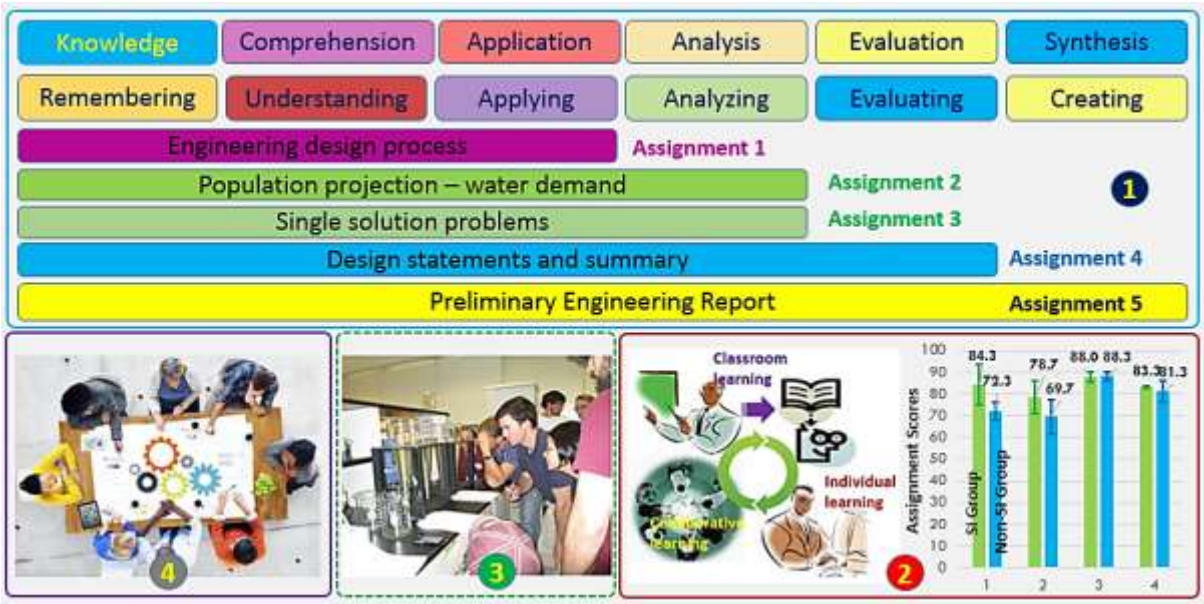


Fig. 1. Critical thinking enhancements through (1) writing assignments with varying difficulty and skill levels throughout the semester (in a junior level environmental engineering course), (2) results of supplemental instruction (classroom instruction, independent and individual learning through collaborative and classroom level discussion on a topic of confusion (in a junior level environmental engineering course, 1-4 represent assignments with a standard deviation for 4 semesters, student scores for single solution problems were not included), (3) hands-on laboratory experiments and teamwork and design (in a junior level environmental engineering laboratory course), and (4) project based learning of engineered environmental systems design and management (in a senior level environmental engineering design elective course).

Recent approaches in laboratory instruction

Several approaches can be implemented to achieve the objectives of laboratory course instruction and to promote higher order thinking. Luster-Teasley et al[14] investigated the use of four case studies in a lab course to introduce sustainability and environmental engineering laboratory concepts using a modified-flipped classroom method. Students were given a case story related to the class experiment and asked to research the topic. The in-person lab class started with a discussion of the case and the student's research finding and then students conducted the lab exercise. Pre and post survey data indicated increased self-efficacy for ABET criteria skills and learning gains.

A problem-based learning (PBL) approach was used for an environment engineering laboratory component to provide an applied context to traditional experiments by Hill and Mitchell[15]. Two problems were defined and used to motivate the design of weekly laboratory sessions. A water treatment competition was designed to provide a creative outlet for presenting the final treatment schemes. These laboratory problems provided greater connectivity with the lecture component of the course and included design components, thus shifting greater decision making responsibility to the students than with traditional "recipe-labs".

Karim[16] used a similar problem-based learning method in student groups of 3-4 members in which they carried out two projects that required data collection, literature review, design, and preparation of professional reports. Analysis on survey questions related to students' perceptions and attitudes about PBL approach appeared to be favorable and acceptable as a learning environment for future environmental engineering design courses.

To enable students to concentrate on theory and application of physical, chemical, and biological processes with minimal time spent learning how to use new software packages or instruments, Weber-Shirk and Lion[17] developed customized "Virtual Instruments" (VIs) with a similar design for multiple instruments written using LabVIEW™ to control and acquire data from a UV-Visible spectrophotometer, a gas chromatograph, a 3-axes positioning system, and a pH-ion meter. They reported that the use of VIs helped make it possible to develop a state of the art laboratory from basic concept to full implementation in approximately 1.5 years and students were able to quickly learn how to use new instruments with capabilities designed to meet the specific needs of an Environmental Engineering laboratory and only a small amount of class time was spent explaining how to use the Virtual Instruments. In another study, to reinforce the lecture portion of the course and address the concerns over reflective experiences in cooperative education opportunities in a mechanical engineering curriculum, Peters et al[18] introduced mathworks® simulation exercises. The redesigned lab experiments provided a positive experience for the students while meeting the course objectives. This type of platform may be helpful to meet the objectives of distance education programs remotely which seems to be a recent trend with increasing undergraduate programs being offered online[19].

An approach to improve effectiveness of laboratory instruction

Metacognitive skill is an intrinsic part of science practices, and a range of assessments can be used to investigate laboratory experiences[10]. Metacognition is usually defined using

descriptions such as thinking about one's own thinking, the capacity to reflect upon one's actions and thoughts, or knowledge and regulation of one's own cognitive system[20]. Theoretical models support two main components of metacognition: metacognitive knowledge or knowledge of cognition, and metacognitive skillfulness or regulation of cognition. Knowledge of cognition refers to the explicit awareness of the individuals about their cognition; that is, knowing about things (declarative knowledge), knowing how to do things (procedural knowledge), and knowing why and when to do things (conditional knowledge). Metacognitive skillfulness or regulatory metacognition is the executive component that comprises the repertoire of activities used by individuals to control their cognition while performing a task. Metacognitive regulation is very important because regulatory activities are believed to be integral to the development of problem-solving skills[10]. In addition to enhancing metacognitive abilities, laboratory instruction should also include the goals that aim at improving conceptual understanding, design skills and professional skills. This means a paradigm shift should be considered in many current laboratory instruction methods[21].

Context for the proposed activity

In regular classroom courses, there is a flexibility and time to implement appropriate activities to enhance student learning experience. However, the same for the laboratory instruction is not feasible. Often, time and resources for laboratory instructions are limited. In addition, the level of demonstration that could be executed to practical levels is also hindered by many resource related issues. These factors may inhibit the full potential that could be developed in laboratory instruction. Moreover, students are not given the freedom to explore scientific activity at hand.

Hypothesis and objectives

Considering the aforementioned issues, it is relevant to introduce an exercise that allows students to think beyond the experimental regime. In addition, it is important to encourage students to ask several questions that promote scientific thinking. This helps the students develop an attitude beyond the laboratory instruction. Inquiry in general and in the context of practical work in science and engineering education has the potential to develop students' abilities and skills such as: posing scientific questions, forming hypotheses, designing and conducting scientific investigations, formulating and revising scientific explanations, and communicating and defending scientific arguments. It is important to open the platform for allowing critical thinking to learn scientific principles governing a laboratory experiment which in turn promotes scientific thinking that seeks for *clarity*, *accuracy*, *precision*, *relevance*, *depth*, *breadth*, *logic*, *significance*, and *fairness*[22]. For this, students must be provided with multiple opportunities in the form of exercises. Therefore, we have used a set of questions formulated in "The Logic of an Experiment (miniature guide[22])" to promote scientific thinking in our junior level Civil Engineering students in CE 3801 Environmental Engineering Laboratory course, details of which are provided in the following section. It is hypothesized that students must be given multiple opportunities to develop and improve scientific thinking and metacognitive abilities. These can be instilled by including writing assignments that promote reflective thinking which promotes scientific thinking[23]. Metacognition can be instilled by first asking questions on a particular topic and then by using the same technique on one's own thinking and rationale for conducting experiments and solving engineering problems.

CE 3801 Environmental Engineering Laboratory Course

CE 3801 is a junior level Environmental Engineering laboratory course[6]. In this course, student groups (four to five members per group) were formed to facilitate team-based cooperative learning. The laboratory exercises included: "Adsorption", "Aeration", "Coagulation-Flocculation-Sedimentation-Filtration", "Chemical Oxygen Demand (COD) and Total Solids measurement", and "Tracer Analysis". In these laboratory exercises, environmental samples from authentic sources were analyzed when possible. For example, the water treatment (coagulation-flocculation-sedimentation-filtration) exercise was conducted using algae contaminated pond water from two different lakes on the campus. Similarly, the wastewater COD and Total Solids measurement characterization exercise used samples of wastewater from various designated process points of the local municipal wastewater treatment plant. Other experiments were conducted using synthetic chemicals such as a dye (i.e., methylene blue) to simulate the environmental pollutants. The students were required to participate in the following assignments.

Approach

The following activities were implemented to instruct the CE 3801 Environmental Engineering Laboratory course and develop a formal process as a framework of operation and to ensure productivity.

- **A problem set assignment**– Students were collectively instructed on issues of laboratory operation and safety. This was followed by a presentation and classical homework design to provide students with a background in experimental statistics, data regression, and experimental design. All work was completed during the first week. This was followed by establishing teams and assigning teams experiments for which they would be responsible.
- **Laboratory exercises –**Students were assigned to teams to work together on each lab exercise. Students were assigned to serve as *team leader* on a rotational basis within the team. Team leaders assumed the responsibility for all aspects of setup and performance of the experiment by their team and, if necessary, coordinate with other team leaders and the instructor or teaching assistant. Student performance as team leader as well as individual participation were considered in assigning final grades. An evaluation rubric was used by the students to evaluate the performance of team leader as well as the team members in the group. Teams were formed with careful arrangement to match student strengths of the subject matter. The teams were assigned at the beginning of the semester.
- **Pre-lab calculations** were submitted on an individual basis and were due at the beginning of each lab session. The calculations involved quantitative parameters to be used during the lab exercises, and as such are designed to facilitate execution of the exercise.
- **Lab reports** presenting experimental results and data analysis were prepared and submitted on an individual basis. Reports should comply with the mini-report format provided, and were due at the beginning of the lab period one week after the exercise was conducted.
- **Group reports and presentations** were prepared after completion of the lab exercises. Each group was assigned to write a full report and make a presentation on one of the lab exercises performed. Reports were submitted prior to the presentations.

- **Site visits** were conducted at nearby public works facilities to provide students with the opportunity to view equipment and operations. Site visit reports complying with the provided format were due one week after the visit is conducted.
- A **final exam** was conducted during the last week of the semester. The exam was administered online and may be taken at the individual students' schedule.

Scientific thinking exercises # 1 and # 2

The following questions were given as an exercise (Scientific thinking exercise I) to evaluate the students' understanding of the laboratory experiments. These questions are framed to allow the students ask questions that link concepts in the course to personal experiences, prior knowledge, and think of controversial ideas in the subject, and develop cases that place students in realistic situations where they must reach a decision or resolve a conflict related to scientific concepts.

Scientific thinking exercise # 1

1. The main goal of the experiment is …..
2. The hypothesis (es) we seek to test in this experiment is (are) …..
3. The key question the experiment seeks to answer is …..
4. The controls involved in this experiment are …..
5. The key concept(s) or theory (ies) behind the experiment is (are) …..
6. The experiment is based on the following assumptions …..
7. The data that will be collected in the experiment are …..
8. The potential implications of the experiment are
9. The point of view behind the experiment is …..

Scientific thinking exercise I included the above set of questions only and exercise II was given along with guiding information to initiate the thinking process for completing the exercise.

Scientific thinking exercise # 2 (together with exercise # 1)

Clarity	Could you elaborate further on your hypothesis (or idea)? Could you give me a more detailed explanation of the phenomenon you have in mind?
Accuracy	How could we check on those data? How could we verify or test that theory?
Precision	Could you be more specific? Could you give me more details on the phenomenon? Could you be more exact as to how the mechanism takes place?
Relevance	How do those data relate to the problem? How do they bear on the question?
Depth	What factors make this a difficult scientific problem?
Breadth	What are some of the complexities we must consider? Do we need to look at this from another perspective? Do we need to consider another point of view? Do we need to look at this in other ways?
Logic	Are all the data consistent with each other? Are these two theories consistent? Is this implied by the data we have?
Significance	Is this the central idea to focus on? Which set of data is most important?
Fairness	Do I have a vested interest in this issue which keeps me from looking at it objectively? Am I misrepresenting a view with which I disagree?

Results and Discussion

Students were asked to participate in the survey by completing the questionnaire while they were actually performing the experiment. The purpose of this exercise was to provide an opportunity for the students to improve their metacognitive abilities by asking right questions at each step. Metacognition helps to ask questions which produce answers required to make critical decisions. Providing exercises that promote metacognition nurtures scientific thinking. Metacognition is thinking about one's own thinking patterns. Scientific thinking requires a level of metacognition to release one's own misperceptions of a subject or a topic. First the set of questions were given without any guidance information. The participation was voluntary. Results are shown in Fig. 2, 31 out of 80 students participated in the first round of the exercise (I). This sample represented approximately 39% of the total student population. Because the students were not given any directions or clues on how to answer the questions in this exercise, the responses were not quite satisfactory. The average grade was 71%. However, the guidance information (guiding questions related to the scientific components as shown in scientific thinking exercise #2) was provided in the second exercise which helped students to answer the questions better resulting in an average grade of 82%. Most students that participated in the first exercise participated in the second exercise and the sample size was 30% of the student population. The quality of responses improved significantly in the second exercise because the guidance information was used to answer the questions. This information helped students ask right questions which promoted scientific thinking seeking for clarity, accuracy, precision and so on.

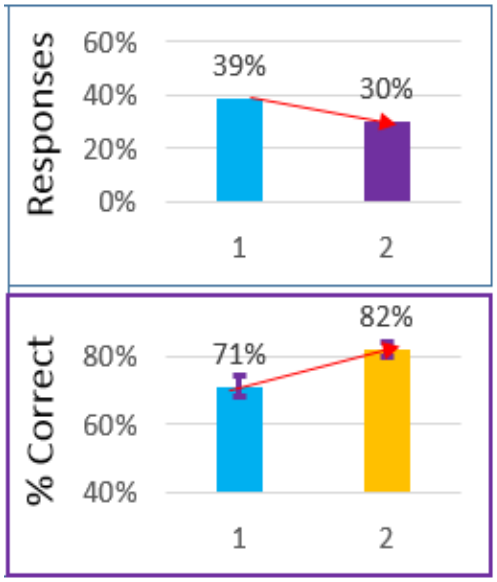


Fig. 2. Responses from students for scientific thinking exercises 1 and 2.

It was still unclear from this data whether students really have an idea of what scientific thinking is. In a third exercise, a set of questions were prepared around the nine core aspects of scientific thinking (clarity, accuracy, precision, relevance, depth, breadth, logic, significance, and fairness). The exercise was made mandatory. Questions, student responses and analysis are shown in Table 2.

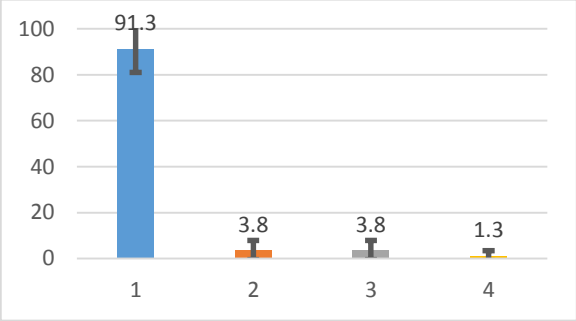
Results of scientific thinking exercise # 3 (Questions and Responses)
Total students – 80; students per session – 20; n = 4 (for standard deviation)

Scientific Thinking and Logic of An Experiment Exercise # 3*

Scientific Thinking

Do you think scientific thinking is important and logical for your laboratory experiments?

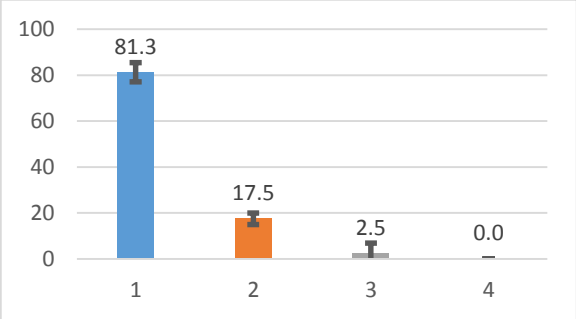
1. Yes, always
2. No, may be sometimes
3. Not always
4. Not sure what it means



Clarity

Do you need a hypothesis for an experiment?

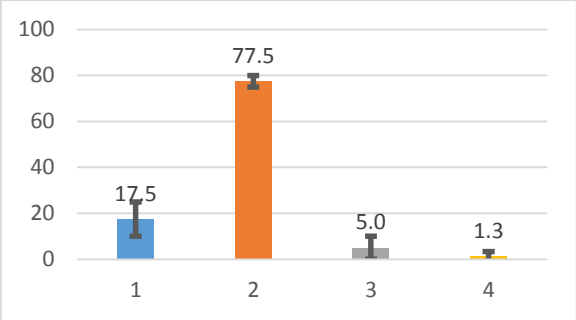
1. Yes, always
2. No, may be sometimes
3. Not sure
4. Not sure what it means



Precision

Are you aware of the fundamental mechanism taking place in the experiment?

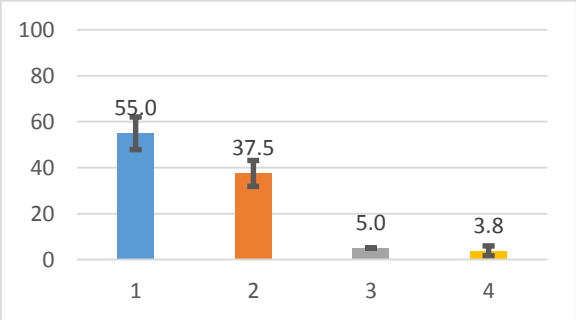
1. I have a complete knowledge
2. Somewhat aware of the expected phenomenon
3. Not sure
4. Not sure what it means



Accuracy

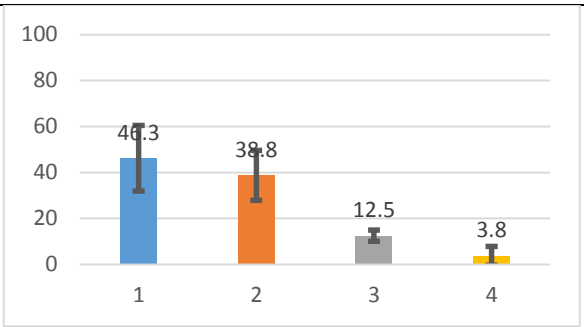
How accurate should your data be?

1. Within 5% error
2. Within 10% error
3. Within 15% error
4. Within 20% error



How do you verify accuracy of your data?

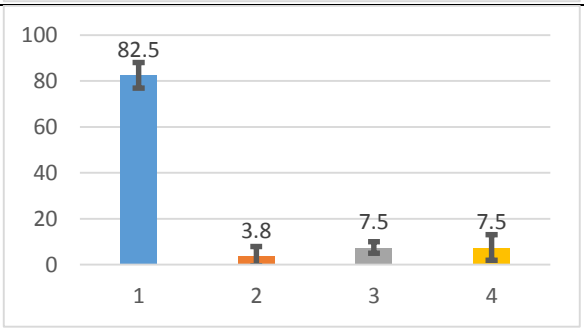
1. Repetitions of the experiments
2. Statistical analysis
3. One well designed experiment
4. Comparing with previous reports



Relevance

Does your data relate to your problem and outcome expected?

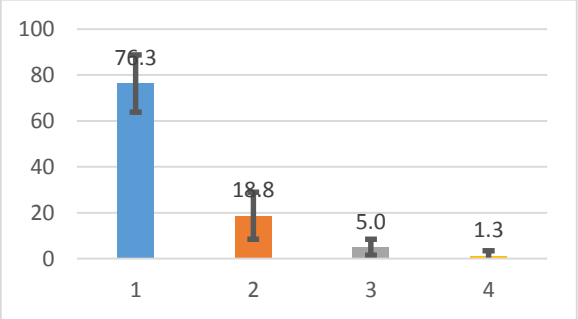
1. Yes
2. No
3. Not sure
4. Not sure what it means



Depth

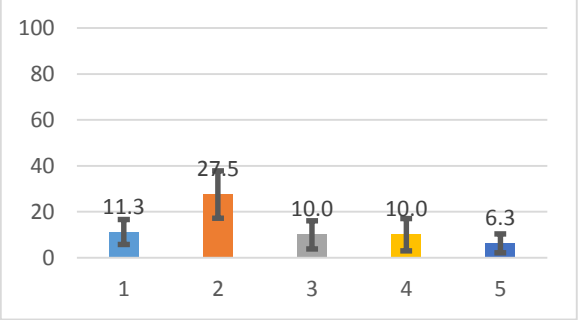
Did you ever wonder if an experiment was more complex than it is designed?

1. Yes
2. No
3. Not sure
4. Not sure what it means



If so, what was that experiment?

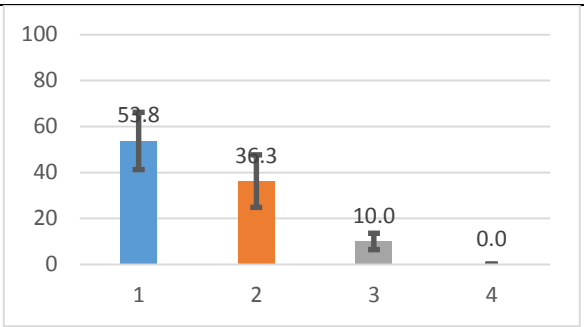
1. Aeration and gas transfer
2. COD and TSS analysis
3. Turbidity removal
4. Adsorption
5. Tracer analysis



Breadth

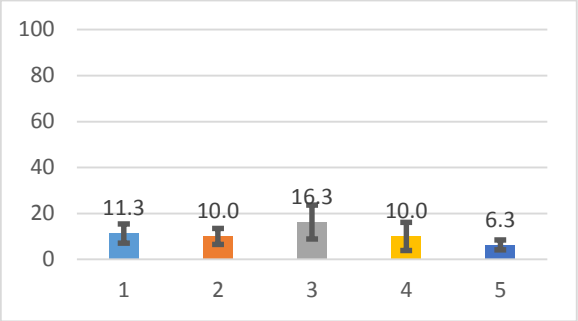
Did you ever wonder if an experiment could be performed in a different way?

1. Yes
2. No
3. Not sure
4. Not sure what it means



If so, what was that experiment?

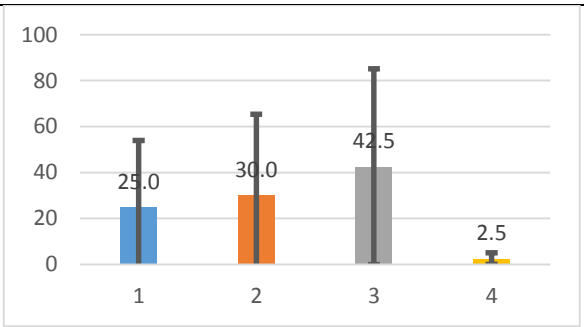
1. Aeration and gas transfer
2. COD and TSS analysis
3. Turbidity removal
4. Adsorption
5. Tracer analysis



Logic

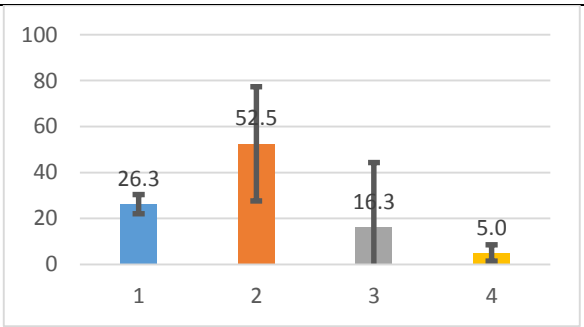
Was the data consistent in your experiment?

1. Always
2. Never
3. Within acceptable limits for deviations
4. Not sure what it means



Did the data present a logic for your experiments between theory and outcome?

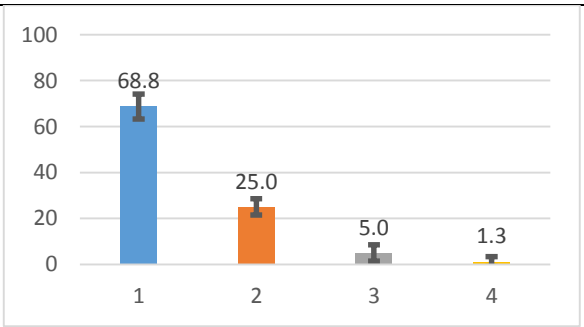
1. Always
2. Never
3. Within acceptable limits for deviations
4. Not sure what it means



Significance

Was the significance of your experiment to the field clear?

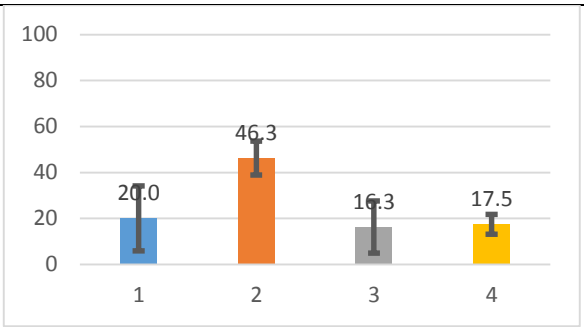
1. Yes, always
2. No, may be sometimes
3. Not always
4. Not sure what it means



Fairness

Have you ever had a difficulty to represent your data from the experiment?

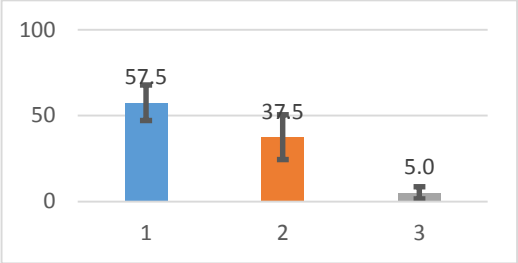
1. Due to your view of understanding of the concept
2. Due to your view of misunderstanding of the concept
3. Objective assessment
4. Not sure what it means



Subject

Is environmental engineering a subject of your interest?

1. Yes 2. No 3. May be



*note – some questions require multiple responses.

The questions about scientific thinking and seeking clarity received more favorable responses. Almost 95% students said they were somewhat aware or aware of the expected phenomenon in the scientific experiment. Majority of students (77.5%) mentioned that they are somewhat aware of the expected outcome. The accuracy of the data question was answered by a good number of students between 5 and 10% acceptable limits. In addition, repetition of experiments (duplicates or triplicates) or statistical analysis was mentioned as a preferred method for validating the accuracy of experimental results.

Most of students mentioned that at least one experiment was more complex than it is designed in the current method. It is a good sign that the students are able to identify the strengths and limitations of current experimental methods. This response also correlates with the question asked for breadth. Most of the students mentioned that the data collected from the experiments was within acceptable limits for deviations. More than 50% of the students mentioned environmental engineering as a subject of their interest. This is somewhat uncommon. A general trend is about 25% in our program and other similar programs.

Student composition and participation

There were 20 students in each laboratory session. Among the four laboratory sessions, 95% of students in session 2 participated in at least one of the scientific exercises while sessions 1, 3 and 4 had participations of 35%, 30%, and 10% respectively. We do not have an explanation on this outcome. The participation of women in sessions 1 through 4 were 29%, 100%, 75% and 50% respectively which were consistently higher than men's participation in sessions 1 through 4 of 38%, 94%, 19%, and 0% respectively. It is interesting to note this trend. The national engineering student statistics by American Society for Engineering Education in 2016 reported that environmental engineering discipline had a high percentage of women participation which is 47.4% while overall engineering enrollment is around 20%[24].

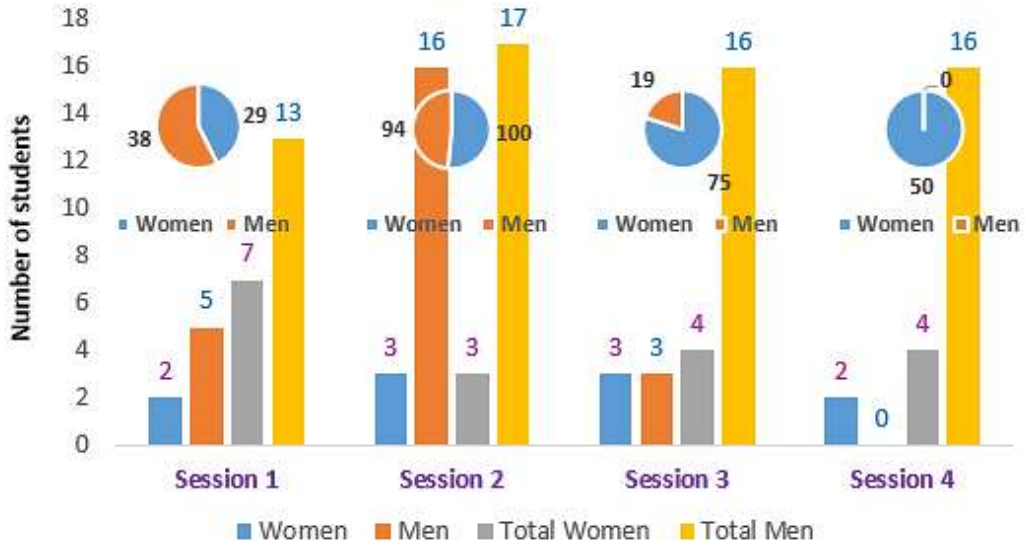


Fig. 3. Student participation by gender in scientific thinking exercises I and II

Limitations of the present work are that students were asked to participate in scientific thinking exercise on a voluntary basis. This is a major limitation because only 40% of responses were gathered in the first two exercises involving evaluation of scientific thinking characteristics. It would be beneficial to make it a required exercise for the students so that a more detailed analysis can be performed as in the case of scientific exercise III survey in this study. Current analysis is also limited by the number of exercises given to the students. Continued use of these exercises in future laboratory courses could help derive better insights into learning experiences of the students. In addition, combining these exercises with a real-world case study or virtual laboratory experimental analysis focusing on recent and contemporary environmental issues could enrich student learning experiences in the laboratory course.

Conclusion

Scientific thinking can play an important role in fostering metacognitive abilities of students to enhance their laboratory learning experience. “The Logic of an Experiment” exercise results show that students have different opinions on the core aspects of scientific thinking. Their responses showed that they have an idea of the expected outcome from an experiment, the purpose of designing and performing the experiment. This exercise has allowed the students to ask questions that they would have never asked themselves when they conduct these experiments. It could be seen from many responses that the students were not sure of what the questions were meant before they were informed about the nine critical areas to guide them answer the questions. This exercise could be a ubiquitous tool to practice scientific thinking not only in the laboratory environment but also can be expanded to the real world professional life to make sound scientific decisions that could yield several benefits to the society and the environment.

References

1. Bloom, B. S.; Engelhart, M. D.; Furst, E. J.; Hill, W. H.; Krathwohl, D. R. *Taxonomy of Educational Objectives: Part I, Cognitive Domain*; McKay: New York, 1956.
2. Willingham, D. T. (2008). Critical thinking: Why is it so hard to teach?. *Arts Education Policy Review*, *109*(4), 21-32.
3. Jacquez, R., Gude, V. G., Auzenne, M., Burnham, C., Hanson, A. T., & Garland, J. (2006). 2006-2175: integrating writing to provide context for teaching the engineering design process. 113rd ASEE Annual Conference & Exposition, Chicago.
4. Jacquez, R., Gude, V. G., Hanson, A., Auzenne, M., & Williamson, S. (2007, June). Enhancing critical thinking skills of civil engineering students through supplemental instruction. In *ASEE Annual Conference & Exposition in Honolulu, Hawaii*.
5. Gude, V. G., & Truax, D. D. (2015). Methods to Instill Critical Thinking in Environmental Engineering Students. 122nd ASEE Annual Conference & Exposition, Paper ID #12224
6. Gude, V. G., & Truax, D. D. (2015). Project Based Learning of Environmental Engineering Principles. 122nd ASEE Annual Conference & Exposition, Paper ID #12341.
7. Hofstein, A., & Mamlok-Naaman, R. (2007). The laboratory in science education: the state of the art. *Chemistry education research and practice*,*8*(2), 105-107.
8. Hodson D., (1993), Re-thinking old ways: towards a more critical approach to practical work in school science. *Studies in Science Education*, **22**, 85-142.
9. Tobin K.G., (1990), Research on science laboratory activities; in pursuit of better questions and answers to improve learning, *School Science and Mathematics*, **90**, 403-418.
10. Sandi-Urena, S., Cooper, M., & Stevens, R. (2012). Effect of cooperative problem-based lab instruction on metacognition and problem-solving skills.*Journal of Chemical Education*, *89*(6), 700-706.
11. Domin, S.D. (1999). A review of laboratory instruction styles." *Journal of chemical education*, 76 (4) 543-547.
12. Brown, A. Metacognition, Executive Control, Self-Regulation, and Other More Mysterious Mechanisms. In Metacognition, Motivation and Understanding; Weinert, F. E., Kluwe, R. H., Eds.; Lawrence Erlbaum Associates, Inc.: Mahwah, NJ, 1987; pp 65−116.
13. Schraw, G., Crippen, K. J., & Hartley, K. (2006). Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning. *Research in Science Education*, *36*(1-2), 111-139.
14. Luster-Teasley, S., Hargrove-Leak, S.C., Waters, C. NSF TUES: Transforming Undergraduate Environmental Engineering Laboratories for Sustainable Engineering using the Case Studies in the Sciences Instructional Method. 121st ASEE Annual Conference and Exposition, Indianapolis, IN, 2014
15. Hill, A.J., Mitchell, Z.W. Competitive Problem Based Learning in an Environmental Engineering Laboratory Course, 121st ASEE Annual Conference and Exposition, Indianapolis, IN, 2014
16. Karim, M.A., Project Based Learning of Environmental Engineering: A Case Study, 122nd ASEE Annual Conference and Exposition, Seattle, WA, 2015
17. Peters, D.L., Stanley, R., Hoff, C.J., Casci, J. Redesign of Lab Experiences for a Senior Level Course in Dynamic Systems with Controls, 122nd ASEE Annual Conference and Exposition, Seattle, WA, 2015
18. Weber-Shirk, M.L., Lion, L.W., Virtual Instruments in an Undergraduate Environmental Engineering Laboratory, ASEE Annual Conference Proceedings, 1996
19. Feisel, L. D., & Rosa, A. J. (2005). The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education*,*94*(1), 121-130.
20. Stewart, B. Y. (1988). The surprise element of a student-designed laboratory experiment. *Journal of College Science Teaching*, 269-270.
21. Krivickas, R. V., & Krivickas, J. (2007). Laboratory instruction in engineering education. *Global J. Eng. Educ*, *11*(2), 191-196.
22. Paul, R., & Elder, L. (2001). *The miniature guide to critical thinking: Concepts & tools*. Foundation Critical Thinking.
23. Bean, J. C. (2011). *Engaging ideas: The professor's guide to integrating writing, critical thinking, and active learning in the classroom*. John Wiley & Sons.
24. ASEE Connections 2016. Female Enrollment by Discipline; Teaching Global Development, March 24, 2016.