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Methods to Instill Critical Thinking in Environmental Engineering Students

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Abstract

In this paper, we present three different methods to instill critical thinking skills in civil and environmental engineering students. Writing assignments, supplemental instruction (SI), and interactive and collaborative learning methods were implemented to enhance critical thinking skills of the students in two civil engineering programs. Writing assignments provide a practical context that deepens student understanding and comprehension of the content area. Students develop written communication skills and a process for thinking through and solving civil and environmental engineering problems. Active learning in the classroom and self-directed learning outside of class create opportunities for the students to apply knowledge and identify questions which can be resolved in the SI session. Students follow a set of steps to develop proper questions and find their own solutions by applying critical thinking skills. Finally, project based learning creates interactive and collaborative learning opportunities that promote the logical progression in creative thinking that leads to critical thinking. This paper presents the observations made through these learning methods and provides a platform for discussion on these topic areas. The improvement in students' critical thinking skills were reflected by the quality of the writing assignments and the higher grades obtained by the group of students attending the supplemental instruction.

Keywords
Critical thinking, environmental engineering, supplemental instruction, student learning, technical writing

Introduction

Critical thinking is essentially a creative and constructive thinking process. It is not a matter of evaluating something in a negative sense but rather it is a healthy thinking process[1]. Critical thinking has to be exercised whenever a decision has to be made on a problem that has more than one solution. Critical thinking requires reliable information and evidence, so one can make decisions based on scientific principles. An individual's experience, technical expertise, basic intuition and engineering reasoning are integral parts of a critical thinking process. Critical thinking involves asking well-reasoned questions and evaluating a variety of potential solutions. A small amount of skepticism is required to improve the thinking process and to evaluate the evidence. Judgment has to be made after weighing the pros and cons in a sound manner. In the civil engineering profession, a successful engineer is expected to exercise the critical thinking process before making a decision as thousands of lives may be affected and millions of dollars spent on a design, whether it is a commercial building, a water or wastewater treatment facility, or transportation infrastructure. The safety of people, the environment and overall project cost are key factors considered for the design to achieve its goals.

In principle, critical thinking goes beyond the classroom activities and student assignments. The core critical thinking skills are identified as interpretation, analysis, inference, explanation, evaluation, and self-regulation[2]. These are integral components of a critical thinking process. Critical thinking skills allow one to approach specific problems, questions, and issues with clarity, orderliness, diligence, reasonableness, care (*responsible care*), persistence, and precision.

The Need for Critical Thinking Skills in Environmental Engineering Students

Environmental engineers provide creative and cost-effective solutions to use resources in an efficient and sustainable way, limit the release of contaminants into the environment, develop sensitive techniques to track pollutants once released and find effective methods to remediate impaired resources. They serve as the vital link between scientific discovery, technological development and the societal need for protecting human health and ecological integrity. In the coming decades, environmental engineers will be increasingly called upon to address broader and complex issues of environmental sustainability and resource management. As such, it is urgent to train emerging environmental engineers with adequate critical thinking skills.

This paper provides an overview of three methods to instill critical thinking skills: writing assignments, supplemental instruction (SI), and interactive and collaborative learning. These were applied in two environmental engineering courses: a junior level course (CE 356 - Fundamentals of Environmental Engineering) and a senior level course (CE 4883 – Engineered Environmental Systems) offered in different civil engineering programs. The student learning improvement through the SI sessions was monitored for three consecutive semesters and the results were compared between the SI group and non-SI group students in terms of academic performance throughout the semester. A summary of the experiences and a critical perspective on enhancing critical thinking skills are discussed in the following sections.

Illustrations

Integrating Writing Assignments

"CE 356 - Fundamentals of Environmental Engineering" is a junior course taught in the Civil Engineering department. General course objectives were to learn and apply the engineering design process and develop and apply skills used by successful practicing professional engineers, including critical (reflective) thinking, communication, and documentation. This course taught the fundamental civil-environmental engineering principles for design of conventional domestic water treatment and wastewater treatment systems. One of the primary learning objectives of the course was for the students to be able to apply fundamental civil-environmental engineering principles and perform simple calculations to design water treatment (physical-chemical treatment) and wastewater treatment (physical and biological treatment) systems. The course introduced the students to the general engineering design process and different levels of thinking through various writing assignments including population projection report, design statements and preliminary engineering design report (PER).

In this course a 10-step iterative process for learning the engineering design process was introduced. This foundation was developed through an assignment that required identifying and describing the steps involved in an actual civil engineering design project described in ASCE magazine. This exercise helped students understand the critical thinking skills an engineer applies in professional practice while developing a product or executing a project. This exercise instilled in the engineering students an understanding that the engineering design process is not a straight-forward step by step procedure but it is an iterative, creative and conscious based exercise. Following this exercise, the students were asked to estimate the population growth for a design period for a given municipality. The population projection exercise involved city characterization (historical, geological, community, industrial sectors), a twenty year population projection developed from census data and different growth characterization models, water resources available, present source of water supply and conservation practices, future water demands, and capacities for a new treatment facility. As a result of this exercise, a population projection report was developed with details on the national and state level regulations and policies required under the Safe Drinking Water Act (SDWA)[3].

Design principles and the design process of water treatment and documentation of the process were built on the foundation of the engineering design process and were taught through an open-ended, team-based project approach. Design statements for the key components of the water treatment process were developed in a short writing exercise. The final assignment was to design the four unit components of the treatment plant, prepare preliminary engineering drawings of each unit operation, as well as a layout of the entire water treatment facility which shows the integration of the individual unit operations into a single treatment plant. The design work was bound as a preliminary engineering report which included a letter of transmittal to the city engineering staff, an executive summary of the design, and an engineering report summarizing the population and water use histories of the city, the alignment of their design with national and state level requirements of the SDWA, and a summary and persuasive justification for the decisions made in their technical design. The report included an appendix which documents the design calculations and preliminary engineering drawings of individual unit operations.

The course required students to perform at a variety of cognitive levels as classified by Bloom's taxonomy[4]. In engineering practice, especially in the engineering design process, higher–order thinking is required. Too often junior engineering students are accustomed to learning material at levels 1 through 3 on Bloom's taxonomy scale (knowledge, comprehension, and application). The assignments in this course were created to facilitate student development as a future professional engineer by working at the six cognitive levels of Bloom's taxonomy and also some ABET criteria (student outcomes a, c, e, f, g, h)[5]. These assignments led to progressive, step-by step growth in the students' learning from level 1 to level 6. By the end of the course the students are learning and working at the highest level on Bloom's scale. Table 1 summarizes the Bloom's classification for the various assignments.

Table 1. Assignment Classification Based on Bloom's Taxonomy.

Assignment	**Bloom's Taxonomy Level†**					
Description	1	2	3	4	5	6
1) Engineering design process	✓	✓	✓			
2) Population projection/Water demands	✓	✓	✓	✓		
3) Single solution problems	✓	✓	✓	✓		
4) Design statements/summary	✓	✓	✓	✓		
5) Preliminary engineering report	✓	✓	✓	✓	✓	✓

†1. Knowledge (list, recite, reproduce), 2. Comprehension (explain, paraphrase), 3. Application (calculate, solve, determine, apply), 4. Analysis (classify, predict, model, derive, interpret), 5. Synthesis (propose, create, invent, design, improve), 6.Evaluation (judge, select, critique, justify, optimize)[4]

Supplemental Instruction

The goal of supplemental instruction is to enable the students to apply skills used by successful practicing professional engineers and exercise critical (reflective) thinking in solving the engineering design problems[1]. SI exercise guides the student's development of critical thinking skills through identifying confusion or lack of understanding of course content and environmental engineering concepts, asking clear and well thought-out questions, and establishing a process for developing and evaluating answers to their own questions. The SI session is designed to develop this skill by applying collaborative learning methods. The SI session meets once per week to resolve student's questions in the topics of water and wastewater treatment. The students work in groups and strive to develop solutions to their questions using problem solving methods typically applied by practicing engineers. The facilitator for the SI session is a graduate teaching assistant (TA) majoring in environmental engineering. The TA typically serves as an SI facilitator for 3-4 consecutive semesters. The first semester, the TA is required to attend all class sessions to learn the content of the course and to identify areas of concern where students may have difficulty by observing student-to-student and student-to-instructor interactions that occur during class.

Prior to meeting in the SI session, students submit questions on the engineering and design concepts discussed within the previous week of class. Active learning in the classroom and self-directed learning outside of class create opportunities for the students to identify questions which can be resolved in the SI session.

The first step of the SI assignment is to construct a question that is comprised of the following four parts:

- Clearly describe the confusion or lack of clarity on the topic of discussion during the past week
- Why is this aspect of the topic confusing or unclear? Explain the specific details that are not clear
- Describe the "engineering intuition" that you can apply to this concept that will assist you in developing logic or rationale that will guide you to a description or answer clarifying the confusion
- What knowledge and background from other classes or practical experiences can you draw on to help yourself resolve this confusion?

Additionally, the students use the textbook (or other appropriate sources) to find information that can be used to clarify confusion and cite a specific reference in the book (cite all of the following that apply: chapter and section numbers, paragraph, figure or table number, and page number), summarize or paraphrase the findings, and apply the information to clarify the confusion.

SI Session – Mix of Collaborative Learning Techniques. The actual method that students apply to learn critical thinking is a mix of approaches that follow a progressive pattern. Progression from individual learning, to small group learning and classroom level learning provides a good opportunity for discovering various aspects of a topic. Each group is assigned one question for a 15-20 minute discussion period. As the groups review their questions the facilitator observes the discussion to ensure that the students are engaged in developing an appropriate response to their questions. When deemed appropriate, the facilitator may interject comments or questions that will guide the discussion toward a constructive outcome. Each group elects a leader, a note-taker and a reporter. Most of the time, the volunteers rotate freely without dominant repetition. The facilitator sometimes appoints the leader and reporter in order to give an opportunity to all the students to participate effectively in discussion. The reporter takes notes of the relevant outcomes while the leader leads the discussion by asking fellow members questions and also contributing to the discussion.

As the course requires the students to exercise critical thinking which is a higher order thinking and learning, it becomes necessary to evaluate the student performance on the basis of Bloom's levels of learning. Students improved grades by participating in the SI sessions (Fig. 1). It should be noted that the grade improvement from B to A is observed to be common and the percentage of grade improvement is acceptable which does not skew the overall grade of the class. Students who achieve a grade of A without attending the SI sessions, but who voluntarily attended and earned the bonus points, are not reported in the analysis because an actual grade improvement was not measured. The data primarily indicate that students who utilized the opportunity and are hardworking by nature have progressed to a higher grade. Though this study evaluated the performance of the SI and non-SI groups based on monitoring work examples and grades, a pre and post SI assessment will be considered to evaluate the effectiveness of the SI sessions in improving a student's critical thinking skills in future research.

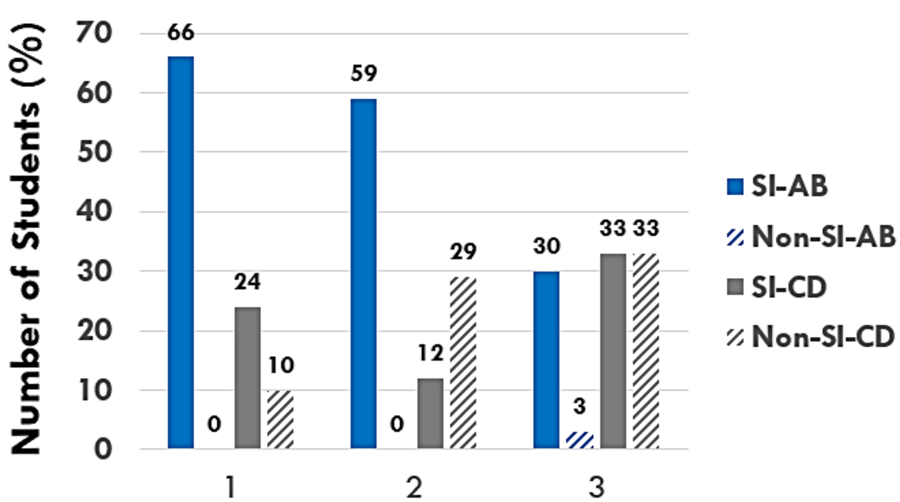

Fig. 1. Student grade comparison between SI and non-SI groups (Note: 1, 2, and 3 refer to semesters; AB- students receiving A or B grades and CD- students receiving C or D grades)

Collaborative Learning

Project based learning (PBL) is often theorized to promote students' critical thinking, especially reasoning skills through collaborative learning[6, 7]. PBL is anchored by *Student Centered Learning* approach that follows constructivist learning theory principles[3]. In this context, knowledge acquisition becomes one of the prerequisites in developing students' critical thinking ability[8]. According to Winterton et al.[9], knowledge and working memory play major roles in the acquisition of complex cognitive skills. This is particularly true since knowledge is operational and working within a social and attitudinal environment. The development of students' critical thinking ability, however, depends on willingness and an awareness of own thinking (self-reflection), as well as foundation skills as explained earlier[10]. The following illustration describes a project-based critical thinking activity implemented in CE 4883 Engineered Environmental Systems, a senior design elective course and the student experiences and opinions from the evaluation survey (Fig. 2).

SWPPP Exercise

Your consulting firm has been asked to generate a construction storm water pollution prevention plan (SWPPP) for the proposed civil and environmental engineering complex at the Mississippi State University. Assume that the area of the construction site is less than 5 acres. About 93000 ft^2 of the land area is to be developed into a teaching and learning facility with classrooms, laboratories, student/faculty/staff offices, auditoriums and conference rooms. An outline (topography) of the site map and the location details are provided in the handout. Please do the following:

1. Conduct a site visit to identify the pre-construction conditions and research any available documentation on the site at the library and other online sources.
2. Prepare a complete SWPPP for the proposed site development activity which should include "during construction" and "post construction" BMPs for the site.
3. Detailed justification of the chosen "control measures" or "BMPs" for the given site on their purposes.
4. Provide an appendix with important assumptions, calculations, site maps and other pertinent information on the site.

CE 4883-6883 SWPPP Exercise Evaluations

Question 1: As a result of the "Stormwater Pollution Prevention Plan (SWPPP)" assignment, my critical thinking skills are:

1. Worse
2. The same
3. Better
4. Significantly better
5. N/A no opinion

Question 2: The goals of this course and the SWPPP exercise include improving students':

a) ability to use given information and to research for available resources;
b) critical thinking and decision-making skills;
c) team work and communication skills;
d) understanding of environmental engineering and management principles;
e) knowledge about engineering professionalism/ethics;
f) understanding of engineering design and practice;
g) ability to use the computer tools such as Excel and stormwater design tools

The SWPPP exercise was:

1. Effective in achieving one or more goals described above (identify and list items)
2. Not effective in achieving one or more goals described above (identify and list items)
3. N/A No opinion

Fig. 2. Storm Water Pollution Prevention Plan (SWPPP) exercise and the evaluation survey

The students' responses are shown in Fig.3. Among the 30 respondents, about 73% (22 out of 30 respondents, Fig. 3a) of the students answered that SWPPP exercise improved their understanding environmental engineering and management principles. About 37% (11 out of 30 respondents, Fig. 3c) answered that this exercise improved their critical thinking skills while 40% (13 out of 30 respondents) of the students mentioned that their critical thinking skills were the same after the exercise. However, majority of the students agreed that SWPPP exercise improved their critical thinking and decision-making skills, and team work and communication skills. Again, 63% (19 out of 30 respondents) of the students responded that this exercise improved their understanding of engineering design and practice which were the main goals of this assignment. A few students responded with the items that were not effective under SWPPP exercise. About ten percent responded that the exercise was not helpful in improving their ability to use given information and to research for available resources (Fig. 3b). They also mentioned that their critical thinking skills were the same after the exercise (Fig. 3d). This is a major drawback with the current learning methods. The students are accustomed to work on single solution problems based on given set of conditions and narrative descriptions. They are disinclined to acquire additional information required to provide a comprehensive solution to a complex problem which is common in environmental engineering design and practice. 53% (16 out of 30 respondents) of the respondents mentioned that their ability to use given information and to research for available resources was improved through this exercise (Fig. 3a).

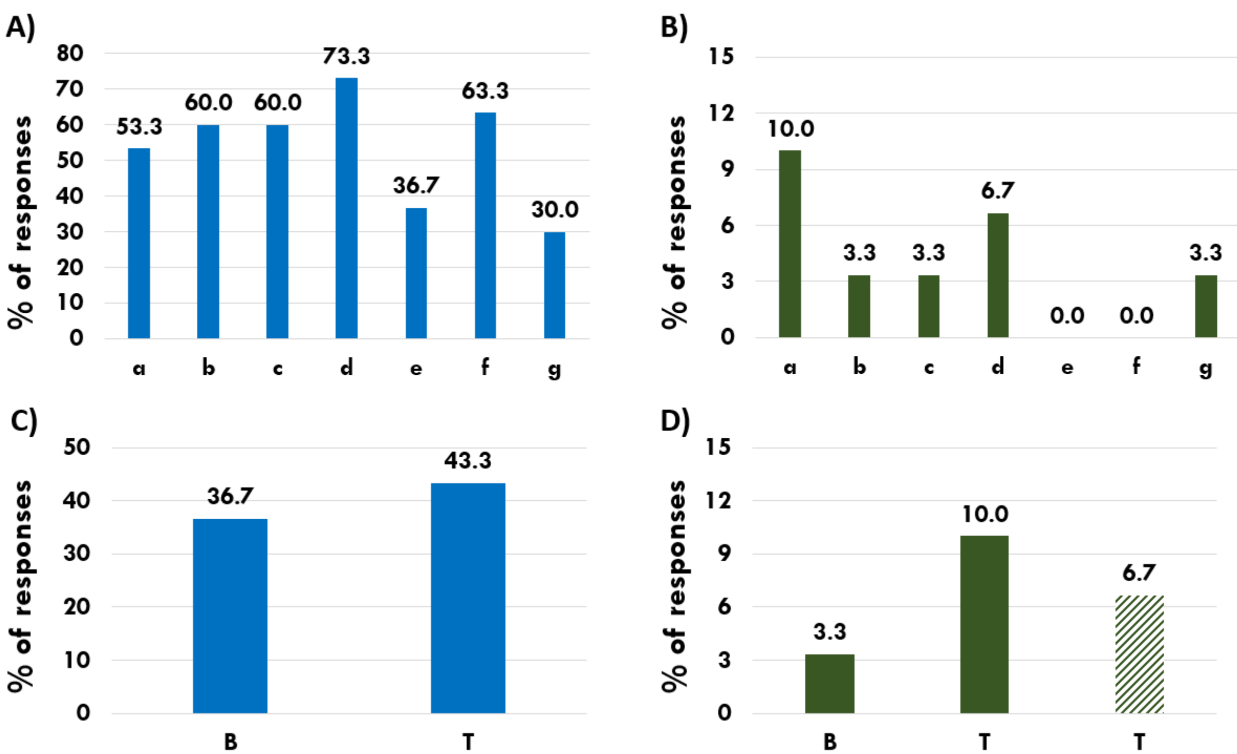

Fig. 3. Student responses to Storm Water Pollution Prevention Plan (SWPPP) exercise evaluation survey (line fill = No opinion; B = better; T = the same;

a) ability to use given information and to research for available resources;
b) critical thinking and decision-making skills;
c) team work and communication skills;
d) understanding of environmental engineering and management principles;
e) knowledge about engineering professionalism/ethics;
f) understanding of engineering design and practice;
g) ability to use the computer tools such as Excel and stormwater design tools)

Conclusions

Various approaches can be considered to instill and enhance critical thinking skills of students in environmental engineering courses. This paper presented three different techniques which were found to be successful at improving critical thinking and engaging students in the learning process. This approach is but one of the important strategies to consider when designing course assignments that encourage the students to think. It challenges students to look outside the routine sources for information while forcing them to be thinking about the problem as they analyze other sources of information. Further exercises to evaluate the student understanding on the critical thinking before and after the SI sessions would be helpful. The project based learning through SWPPP exercise needs to be reinforced with additional relevant assignments that would enhance student critical thinking skills related to the subject matter.

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