Implementing Self-Directed Problem Based Learning in a Multidisciplinary Environmental Engineering Capstone Class

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Abstract
The Department of Civil and Environmental Engineering at The Citadel offers three different capstone classes during the second semester senior year. In an effort to meet ABET 2004-2005 Criteria for Accrediting Engineering Programs Criterion 3(d) requiring students to work in multidisciplinary teams, the department has developed an artificial project that incorporates a “real-world” feel and integrates the three disciplines of environmental, structural, and site development into one unified design team. While enrolled in one of three different concurrently scheduled capstone classes, participating students were required to work effectively across the disciplines as one team. The environmental capstone class was conducted strictly by a self-directed problem based learning (SD-PBL) approach. SD-PBL helps students learn and retain material while developing skills for lifelong learning. During the class, students were required to identify elements of the project which needed to be designed, conduct meetings where students taught students about critical design topics, and ultimately work together within the environmental class and coordinate with the structural and site development classes to complete the design as required. This paper presents the background literature on the SD-PBL pedagogical approach used in this class and the overall methodology behind SD-PBL. Some of the problems and potential solutions related to the interaction between a PBL and non-PBL class, the results of weekly student evaluations and self-evaluation, and a commentary on student involvement both within their own group and across disciplines is included.

Introduction
The Department of Civil and Environmental Engineering at The Citadel offers three different capstone classes during the second semester senior year. In an effort to meet ABET 2004-2005 Criteria for Accrediting Engineering Programs Criterion 3(d) requiring students to work in multidisciplinary teams, the department has abandoned its Senior Research class (used since the inception of the program) and developed an artificial project that incorporates a “real-world” feel which integrates the three disciplines of environmental, structural, and site development into one unified design team. A complete description of the three classes and the interaction between the courses is described in Black et al.1.
In addition to an overhaul of the entire course, the pedagogy of the environmental engineering capstone class was changed from a traditional direct instruction format and laboratory class to a self-directed problem based learning (SD-PBL) approach. This change was motivated by observations made from previous semesters that student-centered learning activities resulted in evidence of more intrinsically motivated students and improved understanding of the topic. Intrinsic motivation is defined by Alderman as the students’ engagement in learning for satisfaction, interest, or challenge of the subject matter. SD-PBL has been shown to result in learning environments that enhance a student’s intrinsic motivation; however, that was not the only reason it was selected as the new environmental capstone pedagogical approach.

PBL has been defined by Norman and Schmidt as a collection of carefully constructed problems that are presented to small groups of students who discuss the issues, identify what is known from prior knowledge and what is not, and seek out information to solve the problem. For the purposes of this paper, SD-PBL refers to a process consisting of self-directed small-group instruction followed by group and self assessment within a design problem context. This paper discusses the following topics:

- Background literature and justification on why the SD-PBL pedagogical approach was used in this class
- A description of the specific methodology of SD-PBL adapted and applied to the class
- Problems and potential solutions related to the interaction between a PBL and non-PBL class
- The results of weekly student evaluations and self evaluation with a commentary on student involvement both within their own group and across disciplines
- Future plans for research and improvements in the environmental engineering capstone class

Literature Review/ Course Development

There were two motivating factors which resulted in the change in the course pedagogy. First, the authors were looking for a better way to incorporate some of the key ABET outcome criteria into the capstone class structure. As part of the department’s improvements in the ABET assessment process, the department determined that the ABET program outcomes identified in Table 1 would be addressed by all of the capstone classes. So, the question at hand was how does the literature on PBL measure up to the ABET program outcome criteria? In the following paragraphs each ABET criteria from Table 1 will be compared to the literature on PBL.

Criterion 3(a) deals with the application of knowledge from the fundamental areas of mathematics, science, and engineering. The research provides two factors, knowledge retention and knowledge application, which are critical to meeting this criterion. Dods conducted a study on senior and junior level students from a gifted school for math and science students. The study compared three different teaching/learning strategies (traditional lecture, PBL, and PBL lecture mix) on the response variables of knowledge acquisition and knowledge retention. They found that lecturing provided a wider coverage of topics, but the PBL strategy promoted understanding and retention of knowledge. The improvement of the application of knowledge from PBL is supported by the concept of knowledge encapsulation as part of expertise development. In a study conducted by Boshuizen and Schmidt on experts, intermediates, and novices in the
biomedical community, they found that experts did not draw on their previously obtained biomedical theoretical knowledge when solving clinical problems but rather simply recent practical clinical experiences. The authors conclude that the expert does not need to use as much mental resources to activate base knowledge because the process is automated. They refer to this placement of base knowledge within the schema of practical procedural problems as knowledge encapsulation. The application in a capstone class is to provide the student with repeated practical problems to encourage expertise development in the realm of practical engineering problems. It should be pointed out that the relationship between PBL and knowledge encapsulation is an untested hypothesis based on previous research, but remains encouraging.

Table 1. ABET 2004-2005 Program Outcomes\(^6\) identified by the department as primary outcomes of the capstone classes.

<table>
<thead>
<tr>
<th>ABET Designation</th>
<th>Description of Criteria: The 21st century civil engineer must demonstrate:</th>
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<tr>
<td>a</td>
<td>an ability to apply knowledge of mathematics, science, and engineering</td>
</tr>
<tr>
<td>c</td>
<td>an ability to design a system, component, or process to meet desired needs</td>
</tr>
<tr>
<td>d</td>
<td>an ability to function on multi-disciplinary teams</td>
</tr>
<tr>
<td>e</td>
<td>an ability to identify, formulate and solve engineering problems</td>
</tr>
<tr>
<td>f</td>
<td>an understanding of professional and ethical responsibility</td>
</tr>
<tr>
<td>g</td>
<td>an ability to communicate effectively</td>
</tr>
<tr>
<td>h</td>
<td>a recognition of the need for, and an ability to engage in, life-long learning</td>
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Criterion 3 (c & f) can be grouped under the overall idea of knowledge synthesis or concept connection. PBL strategies by creation are designed to encourage students to implement a wide variety of subject knowledge. The instructor can control, at least to some degree, the type and variety of prior knowledge required to solve the design problem by altering the deliverables for a given design situation\(^10\)\(^11\).

Criterion 3(d) focuses on a student’s ability to work in groups. Once again group focus is a fundamental aspect of PBL and can be beneficial to the students’ learning in two ways. Evensen and Hmelo\(^3\) points out that group studying has been shown to be more effective than learning alone. The concept of constructive socialization has been used to describe the environments where an individual’s outcomes are affected by others’ actions\(^3\). A study performed by Forbes et al.\(^12\) on the students’ perception of group-based PBL showed that students felt group work was effective at focusing them on the reality of their roles as future clinical practitioners. It is reasonable to assume that students whose educational strategy focused on group interactions and believe they are preparing for their eventual career roles are more prepared to work in group environments that mimic real world conditions. The second benefit stems from the discovery of the individuals’ roles in the group. In self-directed problem based learning, students are
responsible for identifying what is unknown and teach each other new information. This will require students to break up group work into individual tasks, learn information on their own to help with the problem solving, and report their findings back to group members. Through the course of this process, students work in the role of leader, learner, teacher, and facilitator. By working in all of these roles, a student is more prepared to understand group dynamics as well as benefit from the constructive socialization.

Criterion 3(e) focuses on a student’s ability to formulate, identify, and solve engineering problems. Once again ill-structured problems are at the heart of the PBL strategy. Stepien and Pyke\textsuperscript{10} identify a well-crafted problem as one that requires the students to struggle with their reasoning process until they are capable of defining the problem and constructing an appropriate solution strategy. When the design projects are designed from this standpoint and based on real life conditions, it is reasonable to assume students will be prepared to perform in the work environment.

Criterion 3(g) focuses on a student’s ability to communicate effectively. Woods\textsuperscript{13} outlines eight tasks associated with solving any group-oriented task. Woods points out that after the group has identified the new knowledge group members need to learn, the knowledge is divided up among the group members who then go off to learn the knowledge on their own. After knowledge acquisition is complete, the students must return to the group and present their findings. This process requires that all group members develop effective communication skills. At the completion of the teaching session, each student is evaluated by the others in the group, which can result in the identification of strengths and weaknesses. The instructor is available to provide recommendations on better communication practices. This peer-oriented review and evaluation process can result in improved communication skills.

Criterion 3(h) focuses on a student’s ability to recognize the need for and to engage in life-long learning. This ABET criterion is highly linked to the second major motivating factor which resulted in the change in the course pedagogy. After the authors of this paper reflected on the students and their own consulting experience, it seemed that many of the graduates were missing the processing skills and the ability to be effective self-regulated learners in the work place. A comparison of some of the literature on self-regulated learners and SD-PBL may shed some light on the effectiveness of the pedagogy on developing self-regulated learning skills and ultimately lifelong learning.

Zimmerman\textsuperscript{14} defines self-regulated learners as students that are metacognitively, motivationally, and behaviorally active participants in their own learning process. The key words to SD-PBL are metacognition and motivation. Brown\textsuperscript{15,16} states that metacognition is made up of two elements: knowledge of cognition and regulation of cognition. As defined in Bruning \textit{et al.}\textsuperscript{17}, knowledge of cognition is divided into declarative, procedural, and conditional knowledge which a student has been developing and continually refining throughout his/her academic career. The part on metacognition where SD-PBL can make the biggest impact is in regulation of cognition. Again Bruning \textit{et al.}\textsuperscript{17} states that regulation of cognition is made up of planning, regulation, and evaluation. Woods\textsuperscript{13} identifies that a critical step of PBL is self-evaluation. Two opportunities for evaluation are provided for the students. First each week the
students evaluate each other as well as themselves. In addition, after each teach meeting students conduct the same evaluations. In this fashion, each student not only monitors his or her own learning and performance but other students provide scaffolding for the student’s improvement through anonymous evaluation. With this evaluation process, students are improving their metacognitive skills with scaffolding from their fellow student.

Intrinsic motivation to learn material comes from the nature of the “real world” design problem. Literature supports the notion that embellished or contextualized problems can increase a student’s motivation to learn and be engaged in the subject. Lepper and Cardova\textsuperscript{18,19} showed that when assignments were embellished, students were at first more motivated to learn; however, this did not permanently improve or affect their intrinsic motivation. It is also important to improve the student’s attributional beliefs. Zimmerman and Schunk\textsuperscript{20} provide literature that supports the idea that a student’s motivation and self efficacy will improve if the student believes success can be obtained through harder work. Part of any evaluation process is to provide positive and constructive criticism to one’s performance. If the student evaluations are structured such that more positive feedback is required than constructive criticism and that criticism is written in a manner focusing on additional effort in weak areas, then a student’s motivation to improve should increase.

After reviewing the literature on self-regulated learning and how PBL can be related to the ABET program outcome criteria, it was decided that the environmental engineering class would be taught following a model of SD-PBL. The following section outlines the specific classroom methodology used in the capstone class.

Methods
With significant guidance from Woods\textsuperscript{11,13}, Sage and Torp\textsuperscript{21}, Johnstone and Biggs\textsuperscript{8}, and Stepien and Pyke\textsuperscript{10}, the following strategy for SD-PBL implementation was developed for the Environmental Engineering Capstone Class at The Citadel starting the spring semester 2004 and continuing today. The class meets twice a week for approximately two hours a day for a total of 15 weeks. As mentioned previously, a graduating senior cadet must take one of three of the capstone classes (environmental, structural or site development). All three classes meet at the same time and are taught by three different faculty members. The group of environmental engineering students consisted of two male students and two female students out of the graduating class of 19 total students.

The overall class was designed to have a real world feel. The course involved the fictitious interaction with professionals from the surrounding communities (Table 2). A developer contracted the class to develop a fictitious 992-acre tract of land that he had purchased. The project site was to be broken into 25 acre tracts for development as commercial, multi-family or single family developments. In addition, the development was to have a community center with activities building and swimming pool. As part of the developer’s agreement with the city upon purchasing the land, a lot for an elementary school was also to be located in the development area. The utilities (water and sewer) for the entire tract of land were also part of the development agreement. A complete description of the project is discussed in Black \textit{et al.}\textsuperscript{1}. The
Environmental class was responsible for developing the plans, specifications, and cost estimate for the trunk sewer and water lines, an elevated storage tank, an 11 mgd wastewater pumping station and force main, conduct a water quality study to determine the need and location for a booster chlorination station, and made application to the US Army Corp of Engineers for wetland mitigation.

Table 2. Local professionals and government agencies utilized in the real world aspects of the capstone class.

<table>
<thead>
<tr>
<th>Consultant</th>
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<tr>
<td>Developer-Walt Martin—Centex Homes</td>
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<tr>
<td>Architect-John Gardner, AIA</td>
</tr>
<tr>
<td>Regulatory Review Representative—Matt Halter, P.E &amp; L.S.</td>
</tr>
<tr>
<td>Federal Regulatory Review Representatives—US Army Corps of Engineers</td>
</tr>
<tr>
<td>Environmental Consultant—Jack Ellis, P.E.</td>
</tr>
<tr>
<td>Regulatory Review Representative—Bob Horner, P.E. Charleston Commissioners of Public Works</td>
</tr>
<tr>
<td>Geotechnical Engineering Consultant—Dave Hale</td>
</tr>
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</table>

The first four weeks the class met with the developer “client” to go over the desired scope of services. In addition, professionals from the community and regulatory agencies met with the students to give an overview of potential issues and outline the permit application process. The environmental students were required to spearhead the application for wetlands abatement from the US Army Corp. Once the students had met with the required agencies and consultants, the classes broke up to begin designing the project.

The environmental class utilized the following eight steps of problem solving.

1. Explore the problem, create hypotheses, and identify issues, elaborate.
2. Identify what you know already that is pertinent.
3. Identify what you do not know and therefore what you need to know because your lack of that knowledge is impeding the solution of the problem.
4. Prioritize the learning needs, set learning goals and objectives, and allocate resources so that you know what is expected. For a group, members can identify which tasks each will do.
6. Return to the group; share the new knowledge effectively so that the entire group learns the information.
7. Apply the knowledge to solve the problem.
8. Give yourself feedback by assessing the new knowledge, the problem solution, and the effectiveness of the process used. Reflect on the process.

The initial process was modeled by the instructor who covered EPAnet and its usefulness as a design tool. Students were given information on how to write learning objectives and initial
learning objectives for EPAnet where provided. The instructor conducted the first teach meeting. During this process the “teacher” provides concise information on the learning objectives and how they relate to the problem at hand. At the conclusion of the teach meeting, individual and group evaluations were conducted on the professor’s first teach meeting. Students were instructed to provide three positive comments for every constructive comment and, as discussed in the literature review, students were directed on how to write and the benefits of writing constructive criticism on focusing future efforts on improving a specific area. During this first evaluation time, the evaluations were passed around and students discussed how their evaluations compared to each other’s as well as the professor’s.

After the first professor-conducted teach meeting, the students were directed to follow the problem steps on the design problems at hand. For the first few topics, the professor provided guidance on the process but as the semester progressed assistance in this area steadily declined. By the completion of the semester students were conducting teach meetings on their own time and only turning in the learning objectives covered and the evaluations to the professor.

Throughout the remainder of the semester, the professor acted as a facilitator by only answering specific questions posed by the students. In addition, the professor guided plan development. Since a large part of project design is plan preparation and students have little to no experience in this area, examples of how information is presented was done in varying degrees. Typical details, for example, were provided to the students from the local regulatory authority. In the case of a typical plan and profile sheet generation, one example from a similar, but not identical, project was provided.

In addition to the teach meeting evaluations, students were required to conduct weekly evaluations on their performance as well as conducting evaluations on each of their group members. The weekly evaluations were based on those presented by Woods and were evaluated on the basis of the efficient use of time, willingness to listen to other people’s ideas, ability to incorporate other people’s ideas into problem solving, and the degree to which they were considering other aspects of social, environmental, and economic impact. The combined group and individual evaluations were worth 7% of the students’ final grade. A further discussion of the evaluations is provided later in this paper.

The way the class grading was conducted is outlined in Table 3. The project deliverables, as described previously in this paper as well as the final presentation, constituted 65% of the final grade. The students’ job files, biweekly opinions of current event articles and participation in field trips constituted 18%. The evaluations were worth 7% while the midterm was 10%. The midterm grade was divided in an individual scope and a group score. This was done to extrinsically motivate students into caring about other group members learning of the course content.
Table 3. SD-PBL Course Grading Structure

<table>
<thead>
<tr>
<th>Task</th>
<th>% of Final Grade</th>
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<tbody>
<tr>
<td>Project Plans, Specifications, Opinion of Probable Cost</td>
<td>50%</td>
</tr>
<tr>
<td>Job File (i.e. daily memos, phone conversation memos, and any other project documentation.)</td>
<td>10%</td>
</tr>
<tr>
<td>Group evaluations</td>
<td>5%</td>
</tr>
<tr>
<td>Individual evaluations</td>
<td>2%</td>
</tr>
<tr>
<td>Midterm/Quizzes</td>
<td>7% your score on midterm and quizzes</td>
</tr>
<tr>
<td>Participation in scoping meeting, wetlands delineation, and any field trips</td>
<td>3% your group average</td>
</tr>
<tr>
<td>Current events memos</td>
<td>5%</td>
</tr>
<tr>
<td>Final Presentation</td>
<td>15%</td>
</tr>
</tbody>
</table>

Multi-disciplinary interactions

The extent of the interaction between the different classes included coordination of sewer inverts between each 25 acre tract development and the trunk sewer, coordinating water line and hydrant locations, coordinating tract layout with pump station location, coordinating flotation calculations on the wetwell structure, and coordinating the US Army Corp permit application. In all cases, there were no significant problems with the interaction between PBL and non-PBL classes. In a few situations, the PBL class was perceived to be slow to respond to other class needs because a teach meeting was required to confirm that all aspects of the problem were being addressed. This, however, resulted in more concise and accurate answer and other classes learned to appreciate this benefit.

Results from student self-assessment

Both the weekly evaluations as well as the teach meeting evaluations required students to provide a minimum of three positive comments and one constructive criticism. The students completed evaluations for 11 of the 15 weeks. In general, all of the students were extremely open and critical when evaluating their own performance. In contrast, student’s comments maintained an open feel when evaluating another student but were more supportive than critical. Several specific examples of student evaluation comments support improvement in the specific areas discussed in the literature review. The comments received tend to generally fall in four different areas: communication skills, self-directed learning, group dynamics, and general support or scaffolding. In the following paragraphs, excerpts will be presented from the evaluations. When student comments are presented, they are edited only to remove any names and genders.

Comments on communication skills appeared 149 times out of the total of 629 comments provided in the evaluations. In most instances the comments lacked specificity and simply referred generically to communication. As noted previously, one of the reasons why the SD-
PBL learning pedagogy was selected for this class was to improve students’ communication skills. By providing an environmental design project where students were at least extrinsically motivated to care about the fellow classmates learning, it was hoped that students’ communication skills and willingness to listen and make changes based on other people’s criticisms would improve. One specific example appeared in the written comments. At the beginning of the semester, the group and Student A had differing opinions of Student A’s communication skills.

**Student A:** I have been communicating with my team members well.

**Group:** - More effort needs to be placed on improving communication with members of the group.

Later in the semester the student expressed a different opinion of communications skills.

**Student A:** I have been working hard to improve my communication skills and my interaction with other group members.

No other constructive comments were provided for the remainder of the semester dealing with Student A’s communication skills. As a faculty member, the improvement was noticeable and encouraging.

Comments on self-directed learning appeared 107 times out of the total of 629 comments provided in the evaluations. As mentioned in the literature review, self-regulated learners are those who are metacognitively, motivationally, and behaviorally active participants in their own learning process\(^{14}\). In the following passage, Student A seems to be reflecting on the ability to learn and present material.

**Student A:** I don’t know everything I was talking about – I need to research my material more to be better prepared.

Metacognition involves both the knowledge as well as the regulation of one’s own thinking process. In the previous example Student A is reflecting on those processes. In addition, the student seems to be motivated to learn or conduct additional research. In a similar fashion, Student C also seems to be motivated to learn more about the subject.

**Student C:** I would like to know more about different environmental engineering topics.

While it is difficult to identify for sure exactly what the students are thinking at the time of writing these passages; their comments are promising.

Comments on group dynamics appeared 77 times out of the total of 629 comments provided in the evaluations. With any class involving groups and students placed in stressful situations, there are going to be dynamic group situations. The environmental capstone class was no exception.
What was different was that students remained positive and quickly mended any problems. The evaluations reflect some of the students’ thinking on group interactions.

**Student A writing about Student B:** Student B works well with other team members and is better at incorporating other group member’s ideas into a proposed solution.

**Student B:** We all need to work on telling other group members what is going on with our portion of the project.

**Student A on Student C:** Student C is too willing to take on the whole project. Student C needs to delegate more of the work. Student C needs to be more confident of assumptions made.

It is the author’s opinion that if the class environment can remain positive and open then students can learn from difficult group dynamics with little risk to their own ego. The evaluation process seems to provide an instrument to allow students to provide non-threatening criticisms.

Comments on general support or scaffolding appeared 306 times out of the total of 629 comments provided in the evaluations. The biggest surprise in the evaluation process was how supportive the students were with each other. In all cases, students both provided and received extremely supporting feedback from every other student. The following excerpt illustrates some of the support students had for other students’ activities:

**Student C writing about Student D:** Student D was chosen for team leader and has really stepped up to that responsibility. Student D has taken initiative and has made a list of scope of services for the group. Student D is one of the members that is probably the best at analyzing the information received. Student D has a very strong work ethic and displays very good teamwork skills.

**Student C writing later about Student D:** Student D could use some motivation about being excited about the job. Student D has shown some excitement in the past but a little more would be beneficial to the group.

**Student B writing about Student C:** Student C is a very smart person that brings many valuable topics up in team meetings. Student C is very good at computer jobs and displays very good organization skills. Student C relates well with others and is able to work well with the team to get the job done.

The best summary excerpt comes from Student A and captures benefits of the evaluation process used in the environmental engineering capstone class.

**Student A:** I have been working really hard on improving my weaknesses defined by my group.
In addition to written comments, the students were required to provide feedback on a scale of one to five on key areas both for the teach meetings (i.e. quality of knowledge obtained, the quality of instruction, and the amount of follow-up information required by the other students) and the weekly evaluations (i.e. efficient use of time, willingness to listen to other peoples ideas, ability to incorporate other peoples ideas into problem solving, and the degree to which they were considering other aspects of social, environmental, and economic impact). An analysis of these data did not reveal any statistically significant observations. This is partly due to the small class size and the tendency for students to over utilize the higher scores on the scale. The scoring was an effective extrinsic motivator for students who were not performing to the groups expectations.

Future work
The change to SD-PBL learning was successful and will continue to be utilized in the future. From a research perspective, it is unfortunate that the class size is not larger. Regardless, several potential research questions have been raised and will be investigated in future publications. The following is a brief list of a few:

- The usefulness of SD-PBL to affect expertise development in student’s knowledge encapsulation is promising. Properly contextualized problems through the curriculum may result in better equipped graduates.
- The use of SD-PBL to improve student obtainment of ABET program outcomes could be extremely effective. Defendable methods of measuring the effectiveness need to be researched.
- While information was available for the development of this class, additional materials for faculty to assist and encourage PBL implementation into their courses is needed.
- The research on self-directed learning is highly linked to the use of SD-PBL in the class; however, data on the effectiveness of PBL on self-directed learning in engineering education is limited.

Acknowledgement
The authors would like to thank Thomas Dion and Timothy Mays for their enormous contributions to the combined capstone class experience.

References
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