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Project-Based Learning Success in Fundamentals of Fluid Mechanics

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Abstract: A project was introduced at the end of the semester of a fundamental fluid mechanics course four years ago. Since then, the project expanded to start at the beginning of the semester and run throughout the semester with a final presentation on the last day of classes. This project allows for several learning experiences: (1) it increases the ability of students to relate to the material as they select groups based on interest, (2) it increases multiculturalism, as the topics were specifically chosen to be focused on different geographic regions of the world, often with a humanitarian focus, and (3) it allows students creative license in applying what they are learning in the course.

Active learning techniques have been shown to increase retention of historically marginalized students in STEM, as well as to increase retention of learning. Asking students to work on a project that applies the fundamental concepts they are learning in the course forces their understanding to go beyond the textbook. Projects in fluid mechanics include wind turbines, jet engines, water filtration, and artificial hearts. All projects include fundamental elements like flowrate, power in or out, and other characteristics that can be separated into "internal flow" or "external flow."

Groups of three to four students work together the entire semester while learning the fundamentals in class through twelve submissions of a project that overlap with course material. Groups are assigned based on student interest as indicated in a survey before the project was introduced. This ensures that students are being genuine with their responses and not trying to pick their own team. Students meet with the instructor for short meetings every one to three weeks to check on their submissions and discuss why things did or did not work. The entire semester, students are encouraged to understand what the drawbacks of their project are, and in the final presentation, they are to present one conceptual improvement that can be made to their project.

This paper outlines the process and the submissions during the semester. Assessment of project-based learning in the fundamental fluid mechanics course is done through the student end-of-course survey results, analysis of the group project rubric grades, and instructor feedback.

Motivation

The course used for implementation of project-based learning is a Fundamentals of Fluids Mechanics course. It is taught to mostly third-year engineering students in mechanics-based majors at the US Coast Guard Academy. It is a 3-credit lecture course taught in three fifty-minute meetings per week over the course of a 14-week semester. In previous offerings, the course was taught in close alignment with a textbook, with "chalk and talk" lectures filled with theory derivation and examples. The students then completed textbook problems, and in-class exams and a final exam comprised the rest of the student learning assessment. Student learning was acceptable, but retention and ability to apply to more open-ended problems was questionable. As a generalization, many students never became "excited" about fluid mechanics.

They could not relate it to something that they found interesting. The course only existed in their textbooks.

Any fundamental engineering course is easily taught using a textbook for reading and problem assignment and in-class “chalk and talk” lectures to support the reading and problems. This method of instruction is what many engineering students experience but has been shown to not be the most effective at retention or at reaching diverse audiences of students. With the need to encourage diversity in engineering, the engineering curriculum needs to be diversified as well. It was with this motivation that a project was introduced into a Fluid Mechanics course four years ago.

At the beginning of the 20th century, two figures had a considerable influence introducing change to education: Maria Montessori and John Dewey. John Dewey opened his first school in 1896 in Chicago, Illinois, USA, and the first Montessori school opened in 1907 in Rome, Italy, both exposing young children to the idea of learning through doing. The approach of learning through active teaching techniques would not become widely implemented until the 1990s, starting in the K-12 education system [1]. Engineering education, though, is still largely “chalk and talk,” even though project-based learning more closely simulates the work of an engineer in industry.

The ABET Engineering Advisory Council student outcomes also support active learning in the focus on student learning, not instructor teaching. Many of the Student Outcomes correlate closer to Project-Based Learning than traditional coursework, as further outlined in Table 1 [2].

Project-based learning has a natural connection to engineering, as students will graduate to work on projects in the workforce. They will work in small, diverse teams with an end goal. Project-based learning is an effective way to have students apply what they are learning that does not fit the textbook problems: there is no one right answer, often the problem is over- or under-defined, and assumptions need to be made to get to a solution.

As concluded by Mills and Treagust in 2003, project-based learning aligns well with how engineers work in industry, and students, industry, and accreditors all welcome project-based learning over “chalk and talk” methods [3]. The selection of real-world engineering systems has been shown to help students not only with learning but also with confidence in open-ended problems. The selected projects should also support the course learning outcomes [4]. Additionally, project-based learning has implications of improved communication skills, project management skills, design skills, effective teamwork, and professionalism, all tying back to accreditation [5].

Within the context of fluid mechanics, there are many applicable systems. Many other institutions have applied project-based learning to fluid mechanics as well [6], [7], [8]. Almost no fluid system is going to apply only to fluid mechanics and not also thermodynamics, structural mechanics, electrical systems, or other topics. This needs to be transparent to the students from the beginning to avoid frustration. This also requires curated deliverables for each week. For instance, almost all fluid mechanics systems will violate the robust Bernoulli equation, but the application of the Bernoulli equation to a system provides valuable insight. The author researched and selected seven systems to be used in this course, with students divided into teams of three to four students per system. There have been other systems attempted in this course in the past that proved too cumbersome or too nuanced and have since been replaced.

Table 1: Comparison of ABET EAC Student Outcomes, 2022-2023 and Project-Based Learning (PBL) [2].

ABET EAC Criterion 3. Student Outcomes, 2022-2023	**Project-Based Learning Intersection (PBL)**
1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	PBL requires students to approach a complex problem and identify the fundamentals at play
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	PBL is easily applied to societal engineering applications that require consideration of the public good.
3. an ability to communicate effectively with a range of audiences.	PBL is easily assessed using presentations and papers rather than grading homework for the "right answer."
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	PBL is easily overlayed with professional society ethics statements and students' requirement to assess societal impact.
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	PBL is often conducted in small teams working collaboratively.
6. an ability to develop and conduct appropriate experimentation, analyze, and interpret data, and use engineering judgment to draw conclusions.	PBL can be extended from conceptual to experimental, allowing students to evaluate their designs.
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	PBL does not follow textbook examples and requires students to research information from a variety of sources beyond the textbook.

Implementation

Initially, a project was implemented in the last two weeks of the course in the Fall 2019 semester, after all material was covered. Students were asked to apply what they had learned to a modern fluid system. The concern was that students were exhausted from the semester, and only put in a minimal effort on a late project. Additionally, these systems required application of several fluid mechanics concepts. This requires time and reflection.

The group project takes up about one-third of the out-of-class time in the course (about one to two hours a week out of three to six hours of out-of-class time). The other two-thirds are flipped classroom preparation and textbook assignment completion and corrections. There is no in-class time devoted to the project, but there are group meetings with the instructor that may be once a week to once every three weeks in frequency. This forces students to interact with the instructor outside of the classroom, a proven technique for increasing retention of students.

In Fall 2020, 2021, and 2022 semesters, the project was successfully implemented starting the first week of class by assigning students into groups of three to four students based on interest. On the first day of class, a question was asked on the learning management system first day of class survey:

"Fluid Mechanics can be seen in many applications. What applications interest you the most? Please number the topic that interests you the most as one, then 2, 3, etc.

- *Wind Turbine*
- *Irrigation System*
- *Artificial Human Heart*
- *Tidal Energy Device*
- *Water Filtration*
- *Sustainably Fueled Jet Engine*
- *Mars Drone"*

This question allows the instructor to place the students into teams for the following scenarios, with an approach to having students investigate conditions in other parts of the world. This is to implement multiculturalism, a form of diversity, into the project. Figure 1 shows the geographical distribution of the scenarios. Each scenario has a brief statement as to why it was selected.

- Scenario A: Artificial Human Child Heart, Maboneng Heart and Lung Institute, Sunninghill, Johannesburg, South Africa (Internal Flow)
  - This institute was selected because it has successfully implanted mechanical hearts in children in recent years.
- Scenario B: Irrigation System, Subsole, Agrícola Don Alfonso, Atacama Desert, Chile (Internal Flow)
  - This site was selected as it is the driest place on earth other than the poles, yet still has agriculture.
- Scenario C: Wind Turbine, Bac Lieu Offshore Wind Farm, Vietnam (External Flow)

    - This site was selected based on its long coastline with high winds.
- Scenario D: Tidal Energy Device, Offshore Renewable Power Company (ORPC), Igiugig, Alaska, USA (External Flow)
    - This site was selected based on its isolated location and ability to reduce dependence on fossil fuels for energy.
- Scenario E: Sustainably Fueled Jet Engine, Etihad Airways, Abu Dhabi, UAE (Internal Flow)
    - This airline was selected because of their initiative to get to zero emissions.
- Scenario F: Water Filtration, Zulal Water Technology, Tripoli, Libya (Internal Flow)
    - This site was selected because of the difficulty of getting clean water.
- Scenario G: Mars Drone, SENER Aerospace, Tres Cantos, Spain (External Flow)
    - This company was selected because of their work on a current Mars drone.

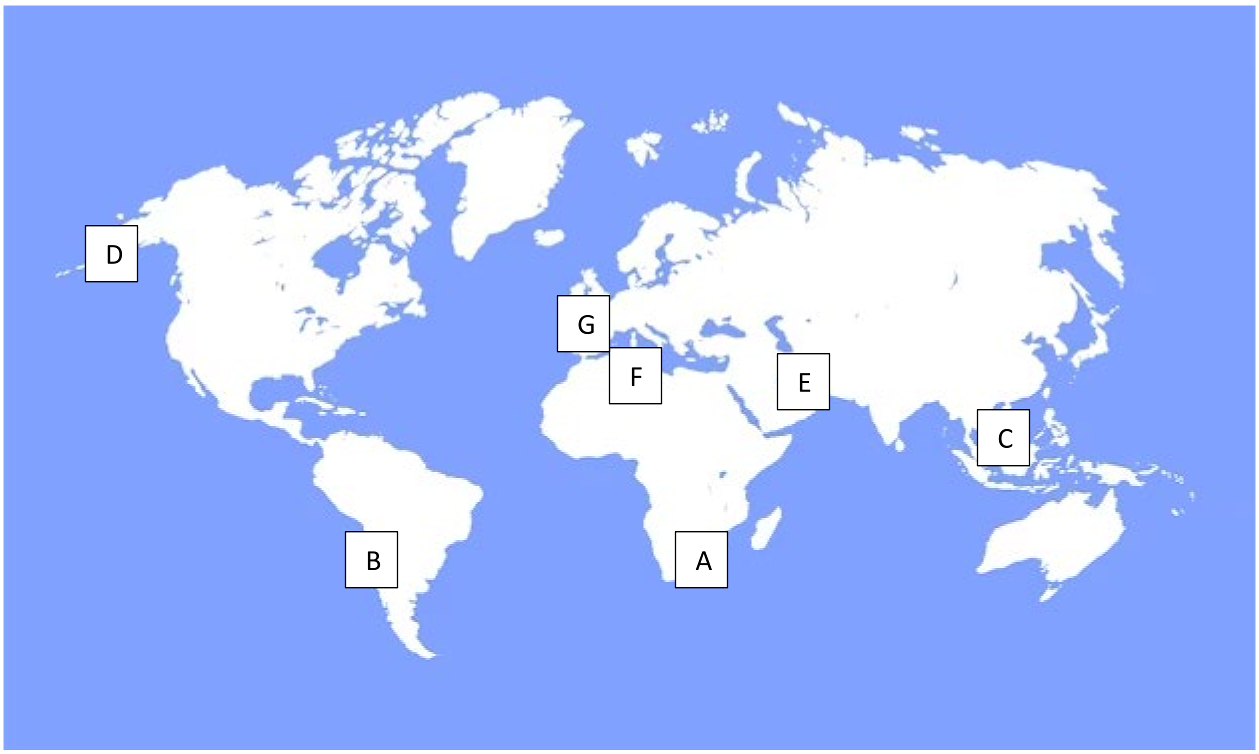

Figure 1: Geographical distribution of group project scenarios, demonstrating the implementation of multiculturalism.

Class sizes vary from 18 to 22 students, and with the variety of interests with which students come, groups have been successfully matched within the top two choices of all the students. With such small course sizes, there is not much room to factor in how best to support diversity within the small groups. Instructor conversations have been had about gender, racial, and ethnic diversity within groups, but the result is grouping based on interest. With a maximum of twenty-two students in a class and four students per group, each class would not exceed eight projects. There is a lot of time spent with groups outside of class, so scaling this to a larger class size would require more instructor time outside of class, and therefore may not be scalable.

The outcome of the project is a concept, so there is no design and build in this course. This allows for the course to forego added cost, facilities, or class time for a lecture-based course. The project objective is to have groups discover how the various course topics apply to their device. The premise applied for the students is that they are entry level engineers working on a team to give a four to five-minute design concept pitch to the “President” of their engineering company at the end of the semester. They are encouraged to do research to sell their concept, and to be creative.

In the final presentation at the end of the semester, their answers to the following question prompts are graded on a rubric to determine their final presentation grade:

1. What fluid principles are at work within your system? Keep track of and report on these in your presentation. Principle names and equations should be used.
2. What are the power requirements/attainments of your system? What type of motor can you use?
3. What are the characteristics of your system that you need to determine? Lengths, flowrates, etc.
4. What other types of engineering or science would you need to incorporate for a successful design? This is called systems engineering, and it can come in many flavors.
5. What are you going to do to make your design unique? This is just a concept, so think of what challenges your topic has, and see if you can get creative about solving how. Feasibility is not a factor here.

Throughout the semester, students have thirteen weekly submissions that align with the topics of the courses. For each week, they must report on more than just an answer. They use an Excel notebook with a tab for each week so that they keep all their information in one place. This also allows them to easily use values from previous weeks on subsequent computations, and to update values as they learn more about the system.

Each week, students are evaluated on the values they calculated, their level of certainty, the questions they bring up to the instructor (no questions imply less thought put into the work), how well the workload was shared across the group, an initiative to go beyond the minimum ask, creativity, and knowing what they are going to look at next. This is outlined in Table 2.

Of note in the weekly submissions are the midterm and final presentations. These were the times for the students to assimilate what they had learned and to communicate this to their classmates, reinforcing ABET EAC student outcome three, to communicate to effectively. Since each group was working on something different, they would not be aware of what the other groups were working on. The midterm presentation was mostly to summarize what their fluid system is and how it applies to fluid mechanics. The final presentation allowed for creativity in that they were to propose something in the design that could be improved.

Table 2: Group project weekly submission outlines as provided to the students.

Weekly Submissions:
Week 1: Team Name, Team Logo, Roles, Overview of current device, Team Agreement. Now that your team has formed and you have your scenario, produce a Team Name, Team Logo (optional), your roles (Facilitator, Timekeeper, Recorder, and Checker), find out what already exists for this type of device in this area, and review and sign the Team Agreement on D2L. Upload your work to the designated D2L Dropbox.
Week 2: Static Pressure Forces for Design. We have learned about static forces now. Your team is to report out a total Force from static pressure of your device. Is your device in sea water? in air? depths? elevations? shape and dimensions? Select a surface of the existing device to analyze the static force on it. Make any necessary approximations to simplify the geometry. Explain your methodology and summarize your final answers.
Week 3: Bernoulli application and Flowrate for your design. Your team must complete an analysis based on Bernoulli's Equation. Select a streamline of interest that will go through your device and see what you know and what you can find. Based on the conservation of mass (Flow in = Flow out) and the Bernoulli Equation, you can only calculate 1 to 2 variables, so you will need to do some research to find reasonable values for others. Keep track of the assumptions for Bernoulli's equation. Do a Bernoulli application and Flowrate analysis. At this point, you will likely violate something about the Bernoulli equation, but try to understand what that violation might be. If you violate it, you may get some crazy answers. Did the energy in your system change? Are there losses that are not being taken out? We will see this come back later.
Week 4: Momentum/Forces for your Design. You will likely use the same two points from last week to draw a control volume with those two points as your inlet and outlet. Now do an analysis of the forces that you expect to have to withstand. If you had corrections to the work from last week, use those corrected values here. What is the meaning of these forces you found?
Week 5: Dimensional Analysis for your Design. You have been looking at this device for a few weeks. What parameters keep coming up? Power, speed, rotation, height… List all these parameters, and develop three or more nondimensional numbers that would be important. Try to stick with those eponymous numbers (vocab word!) from the text, but you may have to produce a new one if you have a parameter that is not common. Hint: EVERYONE should have Reynolds Number in their list. It defines all fluid flow.
Week 6: Midterm Design Presentations/Midterm Student Survey. You have been learning about your scenario for half a semester now, but your classmates have no idea what your group has been up to. Prepare a presentation, 4-5 minutes in length, to explain to your classmates what your scenario is all about. Please do not give them a play-by-play of all your calculations, but the highlights reel? Make your classmates jealous that they are not working on your scenario. After this point, you should be trying to do your calculations more for your modified design than for the original existing design.
Week 7: Energy Analysis & Pump/Turbine for your Design. The first part of this will look a lot like when you did the Bernoulli equation for your flow, but now you know about losses and pumps/turbines. So, now you will do the analysis with the goal of determining how much power you need to put in (or take out). Next, search the internet for reputable pumps or

turbines (generators) that are rated for that amount of power. How do you think you should factor in efficiency of the commercial pump/generator?
Week 8: Pipe Flow for your Design (Excel) (Internal Only). This is a “bye week” for external flow. You have a working Excel spreadsheet for pipe flow. See if you can modify it to work well with your system.
Week 9: Differential Analysis for your Design. We will have learned about Potential Flow Theory and the Navier-Stokes Equations by this time. Which type would apply best to your system? And, for each, what specific type of flow/flows apply? e.g., Potential Flow with a Free Vortex and a Sink, or maybe Navier-Stokes Couette Flow. Explain your decision.
Week 10: Computational Fluid Dynamics for your Design. Computational Fluid Dynamics for your Design - Go to your favorite internet search engine and search for "Computational Fluid Dynamics" and your type of project, e.g., "Computational Fluid Dynamics Irrigation System" or "CFD Irrigation System". Find two pictures that really show something interesting and see what it is all about. Is it showing you velocity, pressure, vorticity? What do the distinct colors represent? Come ready to talk about the two pictures.
Week 11: Drag & Lift on your Design (External Only). This is a “bye week” for internal flow. With the help of the internet, find a drag coefficient and lift coefficient for your device. Do you think those values are reasonable?
Week 12: Finalize your design. Go back and update the previous weeks with your new and improved design. Since you did all your work in Excel, this should be easy. Change the diameter here, a pressure there, and it should all update! Start putting together your final presentation.
Week 13: Prepare Project Presentation. The grading rubric is provided on D2L. Creativity in your design and presenting your information in an interesting way will all get you more points here.

Results

The grade for the group project is based on the twelve regular weekly meetings that last from fifteen to twenty minutes and Excel notebook portfolio completion, but week eight is for internal flow groups only and week 11 is for external flow groups only (10 points each week for 11 weeks) and their group final presentation and ability to answer questions well (50 points).

Table 3 shows the course grading percentages for all components of the course for 2018, 2019, 2021, and 2022, both pre-project and post-project, so that a comparison of individual versus group work can be made. Table 4 shows the project grade, comprehensive final exam grade (the same final exam is given each year, with only minor edits), and overall course grades with averages and standard deviations. For a control, the year 2018 is presented. In 2018, there was no project. Please note that 2020 is not presented as it was during COVID, and the course was taught asynchronously and remotely with a different final exam. In 2019, when the project was introduced, it was worth five homework grades, with homework worth 10% of the course, resulting in a small factor of the overall grade.

The results of the student end-of-course survey from Fall 2022 are presented in Table 5. Figures 2 (a) and (b) represent word cloud responses to the questions “What was most valuable about the group project?", and "What could be improved upon about the group project?", respectively. Word clouds show a word larger as it is used more often in the responses.

Table 3: Grading percentages for all components of the course, 2018, 2019, 2021, and 2022:

	Individual Independent (II), Individual Collaborative (IC) or Group (G)	Fall 2018	Fall 2019	Fall 2021	Fall 2022
Hourly Exam Average	II	50%	50%	40%	40%
Group Project	G	NA	NA	20%	20%
Final Exam	II	20%	20%	15%	15%
Homework Average	IC	10%	10%	10%	10%
Quizzes	II	5%	5%	8%	8%
Case Studies	G	NA	NA	5%	5%
Demonstrations	IC	NA	NA	2%	2%
Creative Expression	IC	+1% Bonus	+1% Bonus	+2% Bonus	+2% Bonus
Demo and Excel Problem	IC and G	15%	15%	NA	NA

Table 4: Comparison of project grades, comprehensive final exam grades, and overall course grades with the implementation of project-based learning.

Year (Cohort size)	Project % of Course Grade	Project Average	Project Standard Deviation	Final Exam % of Course Grade	Final Exam Average	Final Exam Standard Deviation	Course Average	Course Standard Deviation
2018 (80)	N/A	N/A	N/A	20%	79.75%	8.42%	86.27%	4.48%
2019 (52)	1.28%	91.19%	5.79%	20%	76.56%	8.59%	85.41%	5.72%
2021 (78)	20%	94.87%	3.20%	15%	71.47%	11.82%	86.70%	5.41%
2022 (71)	20%	94.23%	10.15%	15%	73.66%	11.4%	87.55%	14.42%

Figure 2: (a) What was most valuable about the group project? (b) What could be improved upon about the group project?

Table 5: Student end-of-course survey responses about the project.

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
The group project was interesting.	8 (25.81 %)	14 (45.16 %)	5 (16.13 %)	2 (6.45 %)	2 (6.45 %)
The expectations for the group project were reasonable.	9 (29.03 %)	17 (54.84 %)	5 (16.13 %)	0 (0 %)	0 (0 %)
I understood how my group project related to the course material.	9 (29.03 %)	19 (61.29 %)	3 (9.68 %)	0 (0 %)	0 (0 %)
I understood how my group project related to real applications of the course material.	11 (35.48 %)	15 (48.39 %)	2 (6.45 %)	3 (9.68 %)	0 (0 %)
The groups were assigned fairly.	11 (35.48 %)	15 (48.39 %)	3 (9.68 %)	2 (6.45 %)	0 (0 %)
The group project grading was fair.	15 (48.39 %)	16 (51.61 %)	0 (0 %)	0 (0 %)	0 (0 %)
Individual effort on the project was equitable.	9 (29.03 %)	16 (51.61 %)	3 (9.68 %)	3 (9.68 %)	0 (0 %)

Discussion

Because of the multicultural aspect of the projects, it is important that instructors from industrialized nations are aware of the issue of the "white savior" and address with students that the project is not to go in and solve all the problems of the project in another country. Young adults are receptive to this idea, and, as engineering students, recognize that they are only going to begin to understand the complexities of the assigned engineering system. They are not there to save a region.

Issues with students still relying on Bernoulli Equation results despite conversations with the instructor about how, with energy being added or taken away to each system, Bernoulli Equation is an incorrect application.

One of the most recurring requests from students is more problem definition. This is because some students are worried more about getting a “right” answer than the learning process. Project-based learning is a valuable tool to relate the theory to applications, taking learning in a fundamental course from the revised Bloom’s Taxonomy third stage of “Applying” to the fifth stage of “Evaluating” and for some students who embrace the call for getting creative, they may reach the top level of “Create.”

As with any group work, there are concerns for equity in the workload and the grading. For this reason, the groups are asked to self-report what percentage of work each student did each week. The instructors encourage the groups that these numbers do not represent an unrealistically even split each week, but that if one group member was unable to contribute significantly one week, that they should take the lead the next week. This transparency and added conversation seem to help; however, more could be done for individual evaluation on the project. This is under consideration in the future. Most students do not mention inequity in grading, though.

Faculty require more practical experience in engineering to relate to project-based learning. Practical experience needs to be rewarded in the promotion process as equal to research activities to encourage engineering faculty to approach engineering more like industry [3].

Student performance on the comprehensive final exam was not seen to improve with the implementation of the group project as a major component of the course. This is in alignment with other research [9]. The gains of project-based learning are not seen during the semester; the gains are long-term. Instructors know their students have taken their learning beyond the textbook, and a timed comprehensive final exam is not going to measure this. This is something measured in follow-up courses and feedback from graduates.

Student learning was evident in the final presentations, and their ability to quickly relate fluid mechanics to many other subjects was evident, increasing the chances of retention. Anecdotally, one group that worked on the wind turbines suggested that the wind turbines be painted purple since insects stay away from ultraviolet light, and therefore the birds would not be attracted to flying into the wind turbines, thus reducing bird kills. Connecting color to bird kills in a fluid mechanics course is at the “Create” level of Bloom’s Taxonomy.

Conclusion

The course grades have shown significant improvement with the implementation of a semester-long group project, while the final exam grades do not reflect this. However, with three years running of the course with the project, it has been noted by the instructors that the students may not retain each lecture topic or the material on the comprehensive final exam, but they can tell you what project they worked on and what things they learned in that project. The benefits of

PBL go beyond one semester. It is retention and application on a larger level; it also allows the students to connect this new knowledge to related subjects, like thermodynamics. Making connections is how we learn and allowing students to connect to real-world applications increases that learning not only in this course but whenever they see the connection.

Not all students appreciate an open-ended problem. Some prefer knowing they got the "right" answer. However, instructors are wiser to prepare their students for what they will be doing on projects rather than making them feel comfortable with the well-defined problems only found in textbooks.

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