Research Article

Problem-Based Learning Impacts Students’ Reported Learning and Confidence in an Undergraduate Biomedical Engineering Course

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Abstract—Recent advances in teaching, many of which incorporate elements of active learning, seek to provide students with learning experiences indicative of real-world problem solving. Problem-based learning (PBL) is one form of active learning that challenges students to address open-ended problems. In this work, we evaluate the efficacy of PBL in achieving the various levels of Bloom’s Taxonomy, compared to the traditional teaching methods of lecture, in-class problems, and homework. In this two-year study of undergraduates at a mid-sized research university, students report their perceived rating of various teaching methods in mastering the educational goals on each level of Bloom’s Taxonomy, from which a cumulative linked mixed model was formed. Students also evaluated their preparedness and increases in skill and confidence for a range of specific tasks associated with completing a PBL project. PBL was the only teaching method to preferentially activate high levels of Bloom’s Taxonomy. Students also reported increases in their skills and confidence ($p < 0.01$), with more time spent on high-level tasks, compared to low-level tasks. Qualitative survey responses indicate a plurality of students found PBL engaging and rewarding, with additional benefits to their development of professional skills. Though PBL is not comprehensively better at addressing all levels of Bloom’s Taxonomy compared to other teaching methods, this work has shown it is far superior at addressing the highest Bloom’s Taxonomy levels of Evaluate and Create. Time spent in PBL improves students’ self-efficacy in high-level tasks, preparing them for difficult and ill-defined tasks they may expect to see in future professional and academic environments.

Keywords—Problem-based learning, Active learning, Bloom’s taxonomy, Self-efficacy, Open-ended problems, Biomedical engineering education.

BACKGROUND

Motivation for Problem-Based Learning in BME Education

Originally signed in 1989, the Washington Accord lays out 12 key skills and competencies that should be attained by all graduates of accredited engineering programs. While these standards were revised in 2014, the central theme has remained steady for over 25 years: “A defining characteristic of professional engineering is the ability to work with complexity and uncertainty, since no real engineering project or assignment is exactly the same as any other.... Accordingly, the attributes place as central the notions of complex engineering problems and complex problem solving". Instructional methods that predominately rely on traditional classroom-based lectures, homework, and tests fail to achieve many of the goals set out in this document and the Engineer of 2020. In the past decade, a renewed emphasis on capstone design and laboratory courses offers students opportunities to synthesize technical knowledge, develop teaming and communication skills, and tackle complex open-ended problems in these few selected courses.

Recent teaching innovations including many forms of active learning have sought to integrate complex problem solving throughout the undergraduate curriculum, thus affording students a more enriching, realistic educational experience. Problem-based learning (PBL) is one form of active learning that challenges student teams to tackle open-ended, complex, ill-structured problems. This focus on concrete problems as initiating the learning process is
central in most definitions of PBL. Known for its ability to develop students’ integrative thinking and evaluation skills, PBL also incorporates professional skills such as teamwork and communication. This paper posits that PBL, when implemented alongside traditional teaching methods, can effectively target all levels of learning, from basic understanding to expert evaluation.

**Bloom’s Taxonomy as a Frame for Learning**

The origins of modern PBL as a teaching method at North American universities can be traced back to a desire for graduates to demonstrate expert-level reasoning and sophisticated integration of knowledge. One established way to describe these different levels of reasoning and expertise is through Bloom’s Taxonomy of Educational Objectives, described by Bloom et al. and visualized in Fig. 1. Since its introduction, Bloom’s Taxonomy has been a cornerstone of educational philosophy. The original framework was revised by Anderson and Krathwohl to arrive at the following action words to describe the levels of cognitive processes: Remember, Understand, Apply, Analyze, Evaluate, and Create. Recognition of Bloom’s Taxonomy or a similar heuristic that differentiates levels of learning has been fundamental to the development of curricula focused on critical thinking, complex problem solving, and the practical application of skills learned in the classroom. While there are alternative, well-validated frameworks (e.g., Reference [23]), we have selected Bloom’s Taxonomy because it is well-established and relatively easy to communicate in a survey format (see Methods section).

In brief, the lowest two levels of Bloom’s Taxonomy are Remember (retrieve or recall relevant knowledge) and Understand (explain ideas or concepts), which are often seen as a necessary precondition for higher levels of mastery. The middle levels of Bloom’s Taxonomy are Apply (carry out a procedure in a given situation) and Analyze (draw connections among ideas). Many engineering courses with “plug and chug” problems operate at the Apply and Analyze levels. The highest levels of Bloom’s Taxonomy are Evaluate (justify a decision) or Create (produce a new work, such as in design courses); these levels are typically seen in experts. We posit that undergraduate engineering students should work at the low, middle, and high levels of Bloom’s Taxonomy, as they develop their technical and design skills.

Bloom’s Taxonomy continues to serve as a resource for educators to ensure that students are meeting learning outcomes that are varied and appropriate for their educational level. Examples of learning outcomes at different levels are as follows:

- Explain the structure and air flow of the lungs (level: Understand)
- Calculate air flow rates in different bronchi of the lungs (level: Apply)
- Create a dynamic mathematical model of the inspiration and expiration of air in the lungs (level: Create).

![Bloom’s Taxonomy](image)

**FIGURE 1.** Bloom’s taxonomy with its six levels. Reproduced under a Creative Commons Attribution license from Vanderbilt University Center for Teaching.
Examining outlined levels of achievement provides an effective reflection for educators to reconsider their curriculum and fill in potential gaps. Krathwohl describes these levels as lying along the cognitive process dimension and orthogonal to another axis, the knowledge dimension. By combining levels of cognition, as described by Bloom’s Taxonomy, with the types of knowledge that may be attained, educators can organize teaching tasks and learning outcomes. The variety of these learning modes suggests that there may exist tasks uniquely suited for high-level cognitive processes, namely Evaluate and Create in Bloom’s Taxonomy. In a pair of papers, Passig argued that addressing high levels of Bloom’s Taxonomy is critical to the future of education.54,55

**Constructivism and Cognitive Apprenticeship Central to PBL**

The hierarchical structure of Bloom’s taxonomy lends itself naturally to the implementation of another educational theory, constructivism. Developed by Vygotsky, constructivism posits that experiential education and reflection allow learners to construct their own understanding of a subject. He argued that to effectively build this competency, learners must work at their Zone of Proximal Development (ZPD), or the level of mastery just beyond the learner’s current skill. Educators can increase students’ time in the ZPD by beginning with significant support and gradually decreasing this support as the student gains their own competency; this iterative approach was named scaffolding by Bruner.8 Considering the sophisticated skills required of modern engineers, educators can implement scaffolding in curriculum to gradually guide students to attaining mastery of a subject, effectively reaching higher levels of Bloom’s Taxonomy. These observations mirror the work of other constructivist researchers, who found connections between learner-constructed understanding and the highest levels of Bloom’s Taxonomy, Evaluate and Create.

Concurrent to the push for constructivist-based learning outcomes was the rise of a learner-based teaching philosophy called cognitive apprenticeship, in which scaffolded guidance is blended with hands-on practice.12–14 Cognitive apprenticeship allows students to simultaneously observe best practices while developing their own skills with coaching, and it is argued to be a core principle for redesigning curricula and education policy to help students achieve “true expertise and robust problem-solving skills”. Continuing to value learner-centered, experiential education, Savery and Duffy argued that a problem-based learning instructional approach effectively prepares learners for real-world problem-solving situations.62 When educators successfully ground all instruction in the context of a larger task or problem, as is the aim with PBL, Savery and Duffy posit that learners are better equipped to take ownership of their own learning and approach problem solving with a more genuine curiosity.

**Implementation and Assessment of PBL in Medicine and STEM Fields**

Begun in medical education many decades ago, PBL was built on insights in educational practice, including constructivist theory, self-directed learning, cognitive apprenticeship, collaborative (or, team-based) engagement, and contextual learning.4,19,28 In medical education, PBL was offered alongside traditional coursework, as a means to support the development of diagnostic and clinical reasoning.4,67 In time, PBL began to permeate fields outside of medicine, including engineering, law, and business.51,65,75 Broadly, PBL is an approach to structuring a course (e.g., Reference [11]) or curriculum (e.g., Reference [25]) that involves challenging students with problems from their expected domain of practice as the stimulus for learning.

Newstetter was among the first to bring a formal PBL structure to both the undergraduate and graduate curricula in biomedical engineering education, and outlined both the theory of PBL in an engineering context as well as suggestions for practical implementation.49,50 In particular, the tutorial cycle provides the structure for student teams to construct their knowledge while solving the problem at hand. The central theme of interdependent teamwork is also described.49,64 Newstetter’s work also emphasized the importance of relevant, ill-structured problems to drive learning.

Assessment of the effectiveness of PBL has been an area of research in medical education, but much less so in engineering education. In a meta-analysis by Strobel and Barneveld,68 most studies were in medical education, and board exams were a common measurement endpoint. Their findings indicated that PBL was superior for long-term retention and skill development, whereas traditional instructional approaches (such as lecture) were more effective for short-term retention. Another article by Dolmans et al.19 reviews papers in the medical education literature from the 1990s and 2000s and argues that PBL is generally effective, although describes efforts that are not.

A notable meta-analysis by Gijbels et al. attempts to evaluate effectiveness of PBL in medical education across three levels: (1) understanding of concepts, (2) understanding of the principles that link concepts, and (3) linking of concepts and principles to conditions and procedures for application.28 Their meta-analysis...
found PBL to be significant for level 2 (high effects size), trending toward significance for level 3 (medium effects size), and not significant for level 1. These papers, along with others,\textsuperscript{1,18} point toward the effectiveness of PBL for developing skills at the middle and high levels of Bloom’s taxonomy, while still recognizing that implementation of PBL as a teaching practice can be uneven, which can affect assessment of student learning outcomes.

In undergraduate STEM education, there are fewer publications on the assessment of PBL effectiveness in achieving goals related to complex problem solving. The Chemical Engineering program at McMaster University has implemented PBL in a four-course series for more than two decades; pooled data from this period has demonstrated a significant improvement in students’ self-reported problem-solving skills from sophomore to senior year compared to negligible changes in a control group.\textsuperscript{76} Examining problem-solving skills empirically in an undergraduate electrical engineering course, Yadav \textit{et al.} found “equal or better [improvement]” in students’ performance on open-ended pre- and post-unit quizzes for PBL units compared to traditional methods.\textsuperscript{77} In a college-level biology course, Carrió \textit{et al.} observed over a 5-year period that students who participated in both lecture and PBL saw improvements in long-term knowledge acquisition and problem-solving skills compared to a control group that just had lecture.\textsuperscript{9}

Additionally, several publications in STEM education highlight the impact of PBL on self-efficacy. In the study of their electrical engineering course, Yadav \textit{et al.} also reported majorities of students responding that the course helped them gain “a lot” or “a great deal” of problem-solving skills and confidence to approach problems.\textsuperscript{77} These prompts asked students to evaluate their improvement with respect to the entire course, which was a mixed lecture/PBL approach; thus, the effect of PBL versus traditional approaches on confidence and problem solving was not distinguished. A similar study, examining students’ self-reported gains in a PBL electrical engineering course, found significant increases in general problem-solving confidence and in ten of eleven subject topics, but failed to compare to a non-PBL implementation.\textsuperscript{46} More support for a significant increase in self-reported problem-solving after completion of a capstone computer engineering course was found by Dunlap, yet with the same lack of a true control treatment to effectively examine the effects of PBL alone.\textsuperscript{20} This study also involved a qualitative journaling component, where students’ responses corroborated the observed increase through a quantitative self-efficacy scale, and most students cited PBL as the key player in these increased skills.

\section*{Impact of Present Work}

In this work, we describe the robust implementation of PBL in an undergraduate biomedical engineering course. This paper explores students’ perception of PBL and other instructional methods on their ability to attain various levels of Bloom’s taxonomy. Through a series of surveys, students reflect and recognize differences between types of pedagogical strategies and their effectiveness as they complete particular learning tasks, such as understanding new material, applying knowledge to novel problems, and creating mathematical models. Students are also reflective on the skills they learned and their effort in these areas. Finally, qualitative feedback links many discussed ideas, including developing self-efficacy and professional skills.

\section*{METHODS}

\subsection*{Description of Problem-Based Learning Within BME 260}

The course BME 260, entitled \textit{Modeling Cellular and Molecular Systems}, is a required course for all biomedical engineering majors at Duke University. The author Dr. Ann Saterbak taught BME 260 in spring 2019 and spring 2020. During those semesters, the author James Long served as a graduate teaching assistant (TA) for the course. The course met twice a week, for 75 min each, as a whole group. In addition, each PBL group met once a week for 60 min with the instructor or a TA. The main textbook was \textit{Bioengineering Fundamentals}.\textsuperscript{61}

For the implementation of PBL in BME 260, we specifically focus on the development of conceptual or “black box” models and related equations that describe biological systems, as well as the insights that can be gained from developing such models. To support the development of these skills, the course learning outcomes for BME 260 are as follows:

\begin{enumerate}
\item State the accounting equation and conservation law and identify the extensive properties that are conserved.
\item Clearly define and apply system definitions, including open, closed, isolated, steady-state, dynamic, reacting, and non-reacting.
\item Apply total and species mass balance equations to engineering systems, including those characterized as open, dynamic, reacting, multi-component, and multi-unit.
\item Apply rate law equations to analyze and solve zero-, first- and second-order systems, including enzyme-mediated and receptor-ligand systems.
\end{enumerate}
5. Apply total energy balance equations to engineering systems, including those characterized as open, dynamic, and reacting.
6. Mathematically model systems (tissue, cellular, and molecular scales) using engineering principles.
7. Work collaboratively on a team.
8. Write and orally present models and their numerical results.

Four different teaching methods were used in BME 260:

- Lecture: The instructor introduced key concepts of the conservation of mass, kinetic rate laws, and conservation of energy.
- In-class problems: Students practiced the material through several forms of active learning, including think-pair-share and in-class problem solving. Short in-class problems focused on understanding terms (e.g., compare/contrast steady-state vs dynamic), applying knowledge to solve problems (e.g., calculate the concentration of a species in a mass balance problem), and predicting behaviors (e.g., predicting the impact of a change in a rate constant on a final concentration).
- Homework: Students turned in homework assignments approximately once per week. Most homework problems were closed-ended and taken from the textbook.
- PBL: Students worked in teams to solve open-ended modeling challenges.

Table 1 shows general tasks that students complete at each level of Bloom’s Taxonomy and the associated teaching methods, as defined by the authors. As a teaching method in BME 260, the instructor used lecture time to lay out material in a structured format. Homework and in-class problems typically focused on understanding content and calculating answers to closed-ended problems, although some in-class problems ask students to make predictions. The instructor administered four quizzes and three exams to assess mastery of the material. Although these assessments were individual, collaboration on homework was encouraged. Exams, quizzes, and homework comprised 65% (2019) or 69% (2020) of the final grade. In contrast, PBL prompts were designed to be open-ended, encouraging students to develop conceptual and mathematical models on their own. Because PBL requires students to numerically solve their developed mathematical models, it also reinforced calculations.

For the PBL modules, students were placed on a five-, six-, or seven-person team and worked with that group for the duration of the semester. At the outset of the semester, a few class periods were dedicated to discussing PBL, modeling strategies, and teamwork. Specifically, students were introduced to the tutorial cycle and were encouraged to frame their discussion around the categories of Facts/Data, Inquiry, Models/Hypotheses, and Assumptions. The first PBL module lasted four weeks, and the second PBL module lasted seven weeks. Given the centrality of PBL, more than one-third of class time was devoted to PBL over the course of the semester.

For each PBL module, students developed multi-unit mathematical models for the prompts given in Table 2. After extensive research in the biomedical literature, student teams created models that were comprised of multiple key units (e.g., pancreas, neurons, lungs, vasculature, etc.). Students selected key chemical constituents (e.g., estrogen, sodium, red blood cells, renin, carbon dioxide, etc.) and mathematically modeled how they moved across and/or reacted within the units. Often, students were asked to develop and compare mathematical models during

### Table 1. Author-identified technical tasks and associated teaching methods in BME 260 for each level of Bloom’s Taxonomy.

| Bloom’s Taxonomy level | BME 260 tasks | BME 260 teaching method(s) |
|------------------------|---------------|---------------------------|
| Remember               | Remember the general form of accounting equation and important terms (e.g., steady-state) | Lecture |
| Understand             | Recognize problem type; simplify equation to fit problem | Lecture, In-class problems, Homework |
| Apply                  | Solve accounting and kinetics equations by computer code or by hand | In-class problems, Homework, PBL |
| Analyze                | Compare and contrast models and numerical answers | In-class problems, Homework, PBL |
| Evaluate               | Determine if model assumptions are valid; check numerical results to see if they make sense | PBL |
| Create                 | Create novel models; write novel equations; choose essential units and chemical constituents | PBL |
typical and diseased states (e.g., HIV-infected cells vs healthy cells). Student teams selected the system, including the units, chemical constituents, and disease, and thus were often excited and motivated to learn about the systems in detail. Full PBL prompts are in Supplemental Material.

The models developed by teams typically included a visual model (e.g., Fig. 2), a series of mathematical equations describing the steady-state and/or time-dependent change in the composition of key chemicals, and computer code that completed the calculations associated with the equations. Model results typically included a series of tables and figures that demonstrated the behavior of the modeled system. For example, a team might show the time-dependent change of blood glucose levels after a meal in a person with and without diabetes. At the end of each PBL module, each team presented a 15 to 20 min oral presentation and wrote a 10 to 15 page report on their developed model and its numerical results. PBL modules comprised 35% (2019) or 31% (2020) of the final grade. In spring 2020, the second PBL was finished in an online learning format. Active, sustained engagement and contributions to a student’s team was assessed through CATME. Students with low CATME scores, especially when corroborated with instructor and TA observations, earned lower PBL grades.

### TABLE 2. Summary of PBL prompts used in BME 260 in 2019 and 2020.

| Year     | Topic of PBL                                                                 | Examples of altered or diseased conditions          |
|----------|------------------------------------------------------------------------------|-----------------------------------------------------|
| 2019, 2020 | **PBL #1 - Modeling Chemical Movement During Signal Transduction:** Develop multi-compartment model of synapse/nerve cell system; track 4–5 chemical components during healthy and altered conditions. | Caffeine, Adderall, Alcohol                        |
| 2019     | **PBL #2 - Modeling the Impact of Molecular/Cellular Diseases on Blood Function:** Develop cellular/molecular model of typical and diseased states in blood; develop multi-compartment model that tracks 4–6 chemicals during steady-state and dynamic conditions. | HIV, Leukemia, β-Thalassemia, Malaria               |
| 2020     | **PBL #2 - Modeling the Mechanisms of an Infectious Disease:** Develop model of typical and diseased states of a virus or parasite in body; develop multi-compartment model that tracks 4–6 biologics during steady-state and dynamic conditions. | HIV, Malaria, Dengue Fever, Rubeola Virus           |

**FIGURE 2.** Example model of glucose regulation in human body. Boxes represent conceptual compartments or organs. The volume of blood as well as concentrations of glucose, insulin, and glucagon are traced through the system. The impact of diabetes can be demonstrated in this model.
Research Questions

This study tested the following research questions in two key areas:

Teaching Methods and Bloom’s Taxonomy

- #1A: To what extent do students identify that different teaching methods and classwork types develop their skills at different levels of Bloom’s Taxonomy?
- #1B: Based on students’ feedback, to what extent are high levels of Bloom’s Taxonomy realized with traditional teaching methods such as lecture and homework?

Specific Tasks in PBL and Bloom’s Taxonomy

- #2A: Do students report increases in skills and confidence with more time on task?
- #2B: Do students report greater increases in skills and confidence for high-level tasks of Bloom’s Taxonomy, as compared to low-level tasks?

Participants and Data Collection

Participants were students enrolled in the undergraduate biomedical engineering course BME 260. Data were used from students in the Spring 2019 semester (n = 42) and the Spring 2020 semester (n = 48) (IRB protocol 2020-0303). Pooled response rate across the 2 years among students responding to all prompts was 83%. Students ranged from sophomores to seniors, although most were sophomores. All students in the 2019 course received a hard-copy post-course survey, and all students in the 2020 course received a hard-copy pre-course survey and an online post-course survey delivered via Qualtrics (necessary due to the pandemic). No demographic information was collected on participants.

While Bloom’s Taxonomy has been extensively applied to support teachers and their instructional methods (e.g., References [15, 66]), fewer studies have turned their attention to student perception of learning in the context of Bloom’s Taxonomy. Without a validated survey in this area in the literature, the team embarked on an exploratory research project to test the above hypotheses and gather qualitative data that could later be used to validate a research instrument. The administered survey had three main parts: Bloom’s Taxonomy and Teaching Methods; PBL Skills Evaluation; and Open-ended Responses. (See Supplementary Material for complete surveys.)

Bloom’s Taxonomy and Teaching Methods

A diagram and basic explanation of Bloom’s Taxonomy was given in the post-course surveys (2019, 2020). The students were asked to consider each teaching method (lecture, homework, in-class problems, PBL #1, PBL #2) in light of Bloom’s Taxonomy. For the course content domains of mass conservation and kinetics, students were asked to reflect upon and answer: How would you rate each teaching method and classwork type in regards to how well each helped you to master the educational goals on each level of Bloom’s Taxonomy? Students’ responses were collected for each level of Bloom’s Taxonomy for each teaching method on a Likert scale of: 1—poor; 2—fair; 3—satisfactory; 4—good; 5—excellent.

PBL Skills Evaluation

In the pre-course survey (2020), students were presented with a list of 14 skills relevant to PBL such as “Finding numbers in literature,” and “Tackling complex problems” (Table 3). While not shared with the students, Table 3 shows the skills based on the authors’ intimate knowledge of the tasks in the context of the course. Aligning with the hierarchical framework of Bloom’s Taxonomy, tasks are sorted to three categories: low-, middle-, and high-level skills. Five skills were less strictly related to technical tasks and more related to working in a team to solve a problem; these tasks were classified as professional skills. For each skill, students were asked to evaluate the following:

A. To what extent were you prepared at the start of the course to complete the task?
B. To what extent do you need practice?

Student responses were on a Likert scale of 1—Not at all; 3—Somewhat; 5—Very much.

### Table 3. PBL skills included on survey. Tasks sorted into Bloom’s Taxonomy level by authors.

| Tasks                              | Bloom’s Taxonomy level |
|------------------------------------|------------------------|
| Understanding physiology           | Low                    |
| Understanding cell/molecular biology | Low                 |
| Understanding conservation laws      | Low                    |
| Researching technical topics       | Middle                 |
| Finding numbers in literature      | Middle                 |
| Technical reasoning                | Middle                 |
| Simplifying complex systems        | High                   |
| Tackling complex problems          | High                   |
| Creating models                    | High                   |
| Coding                             | Professional           |
| Oral presentations                 | Professional           |
| Writing technical documents        | Professional           |
| Teamwork                           | Professional           |
| Project Planning                   | Professional           |
all; 2—To a small extent; 3—To some extent; 4—To a moderate extent; 5—To a great extent.

The post-course surveys (2019, 2020) presented the same list of 14 skills (Table 3) and for each asked students to again evaluate their initial preparedness and their current need for practice as given above, as well as:

C. To what extent has your confidence as a biomedical engineer increased?
D. To what extent has your general skill level or ability increased?
E. To what extent did you spend time on these various aspects during the PBL projects?

Student responses were on the same Likert scale from 1—Not at all to 5—To a great extent, as noted above.

Open-Ended Responses

In the pre-course survey (2020), students were presented with two open-ended prompts, asking them to:

- List the 3 to 4 challenges you anticipate in the PBL projects, and
- List the 1 to 2 things you hope to learn/improve in the PBL projects.

In the post-course surveys (2019, 2020), students were presented with two open-ended prompts, asking them to:

- List the 3 to 4 most frustrating things about the PBL projects, and
- List the 1 to 2 most rewarding aspects about the PBL projects.

Data Analysis

Bloom’s Taxonomy Learning Outcomes

Duke Learning Innovations organized and stripped the data of any identifying information. For mass conservation, PBL #1 and PBL #2 data were coalesced into a single “PBL” category, resulting in double the number of observations as each of lecture, homework and in-class problems. For the kinetics domain, only PBL #2 data was used because PBL #1 did not require the use of kinetics. Reported data were aggregated across both years (n = 90). Means and standard deviations of students’ reported level of Bloom’s Taxonomy activation (1 to 5 Likert scale) were calculated for each combination of content domain and teaching method.

Cumulative Linked Mixed Models for Teaching Methods

To further explore the trends in the data above, two cumulative linked mixed models were created for the content domains of mass conservation and kinetics. A cumulative linked mixed model was selected due to the categorical predictors and ordinal outcomes present in the data. Such a regression approach was preferred over a traditional ANOVA analysis due to the robustness of regression regarding missing and imbalanced data.72 These models were completed with the ordinal package’s clmm function in R.10,52,60,73,74 For mass conservation and kinetics, each model reflected a 4 × 6 fully crossed factorial experimental design, as all students responded for each combination of the four teaching methods and six Bloom’s taxonomy levels.

These models predicted students’ reported degree of mastery as an ordinal outcome based on fixed main effects for each of the teaching methods, Bloom’s level, and pairwise interaction between these two factors’ main effects. Year was also added as a fixed effect to both models, attempting to account for any potential effects on scores from the virtual mode of delivery for some of the 2020 year. Each model included a random effect term with 90 levels, each corresponding to a particular student, to control for the variability between different students. Likelihood ratio (LR) tests comparing each model to null models without random effects demonstrated significance of this random variable (Mass: LR = 678.3, p < 0.001; Kinetics: LR = 751.2, p < 0.001).

Statistical significance of the models was calculated using the emmeans package and the Anova.clmm function from the RVAideMemoire package in R.32,40 Effect size was calculated as the predicted mean of the differences, divided by the standard error of the difference. p values were calculated to indicate the significance of each effect size relative to the null hypothesis of no effect. Post-hoc pairwise statistical tests were conducted to examine differences in mean student response for all pairwise combinations of Bloom’s level, examined separately for each teaching method. These post-hoc comparisons used Bonferroni’s method of controlling for familywise error. For reproducible R source code, please visit https://github.com/evandragich/bme260.

PBL Skills

For each of the 14 skills that students evaluated, means and standard deviations were calculated and reported using post-course survey data from 2019 and 2020 (n = 90). Plots were created from data from three prompts (increased confidence, increased skill, and time spent), omitting skills categorized as professional.
Reported $R^2$ values for the correlation between the scores for increased confidence and increased skill were calculated using the residuals from the line of unity, over all students’ individual data. Statistical significance was computed using a two-factor ANOVA with two treatments: the survey prompt (increased confidence, increased skill, and time spent), and the levels of Bloom’s Taxonomy to which each skill corresponded (low, middle, and high as defined in Table 3). For a conservative approach, variance between subjects was treated as part of the variance due to error. Post-hoc testing was performed on the pairs of Bloom’s Taxonomy levels using Tukey’s HSD test with a Bonferroni correction for familywise error.

Furthermore, the significance between each level was calculated for the individual prompts (increased confidence, increased skill, and time spent) using a one-factor ANOVA and a Tukey’s HSD test with a Bonferroni correction. For example, to evaluate the significance between each level for increased confidence, the responses to increased skill and time spent were removed, and the one-factor ANOVA was performed using only the levels as treatments. This process was repeated for the remaining two prompts. For a conservative approach, variance between subjects was again treated as part of the variance due to error.

Professional skills were separately analyzed with data from two prompts (need more practice, prepared at start), using paired pre- and post-course survey data from 2020 ($n = 48$). Scores for computational coding were omitted because an estimated less than half of the students participated in the coding portions of PBL; most groups delegated coding duties to a subset of their team. However, all other skills were known to be practiced to some extent by most or all students. Here, $p$ values to determine statistical significance were computed using a one-sampled, one-tailed, paired $t$ test between the pre- and post-course responses over the total data set of all professional skills.

**Qualitative Analysis**

For each of the four open-ended response questions, three independent readers assessed the qualitative responses following the listing of PBL skills (Table 3). Readers assigned each student response to between zero and six content categories. As in Elo et al., each reader inductively added new, more appropriate coding categories during this initial round of coding. The readers then met to coalesce these categories into a finalized set of categories for each survey prompt and independently recoded the data following this new rubric. Finally, the readers convened and settled major discrepancies in frequencies, ultimately reporting the median percent of coded statements that referenced each content category, along with a corresponding sample quote. Percentages are reported as a proportion of the total number of coded responses.

**RESULTS**

**PBL Achieves High Levels of Bloom’s Taxonomy**

Figures 3 and 4 show student responses to the question, “How would you rate each teaching method and classwork type in regard to how well each helped you to master the educational goals on each level of Bloom’s Taxonomy?” The mean reported score is plotted by teaching method and level of Bloom’s Taxonomy for domains of mass conservation (Fig. 3) as well as kinetics (Fig. 4).

In Fig. 3a, a positive trend in scores is observed in the PBL grouping, moving upwards as Bloom’s Taxonomy level increases. In other words, students report that PBL was most helpful for mass conservation at higher levels of Bloom’s Taxonomy such as Evaluate and Create. Conversely, a negative trend is observed in the lecture grouping. Here, students report that lecture was helpful for mass conservation at lower Bloom’s Taxonomy levels such as Remember and Understand, but not at middle or higher levels. Students report that in-class problems and homework were most helpful for lower and middle levels of Bloom’s Taxonomy, specifically Apply and Understand.

An alternative way of viewing these relationships is shown in Fig. 3b. Here, there is a positive trend observed in the Create and Evaluate groupings, moving from lecture to PBL. Furthermore, in the Create grouping, PBL is the only method with a reported score higher than the global mean. For the lower levels of Remember and Understand, students report that lecture, in-class problems, and homework helped them achieve these Bloom’s Taxonomy levels; in contrast, PBL is the only method with a score lower than the global mean for these two levels. For the Apply and Analyze groupings, students report that homework was the best teaching method to help them master the educational goals at that Bloom’s Taxonomy level.

Similar trends by teaching method are observed for the kinetics domain, shown in Fig. 4a. A positive trend in scores is observed in the PBL grouping, moving upwards as Bloom’s Taxonomy level increases, although students identify PBL as being impactful for levels of Apply, Analyze, Evaluate, and Create. The positive trend in reported scores with taxonomy level is weaker for PBL in kinetics compared to mass conservation, but the negative trend for lecture is equally pronounced. Again, students report that lecture was helpful for kinetics at lower Bloom’s Taxonomy levels.
FIGURE 3. Average students’ reported activation scores for combinations of teaching methods and levels of Bloom’s Taxonomy for mass conservation topics, grouped by method (a) and taxonomic level (b). Error bars indicate the standard deviation over all students ($n = 90$). Dashed line indicates the global mean over all methods and levels.

FIGURE 4. Average students’ reported activation scores for combinations of teaching methods and levels of Bloom’s Taxonomy for kinetics topics, grouped by method (a) and taxonomic level (b). Error bars indicate the standard deviation over all students ($n = 90$). Dashed line indicates the global mean over all methods and levels.
such as *Understand*, but not at middle or higher levels. Students report that in-class problems and homework were most helpful for lower and middle levels of Bloom’s Taxonomy, specifically *Apply* and *Understand*.

In Fig. 4b, there is a positive trend observed in the *Create* and *Evaluate* groupings, moving from lecture to PBL. Furthermore, in the *Create* grouping, PBL is the only method with a reported score higher than the global mean. For the lower levels of *Remember* and *Understand*, students report that lecture, in-class problems, and homework helped them achieve these Bloom’s Taxonomy levels; in contrast, PBL is the only method with a score lower than the global mean for these two levels. Homework is repeated as the highest scoring teaching method to help them master the educational goals for middle taxonomy levels of *Apply* and *Analyze*.

**Cumulative Linked Mixed Models Support PBL as a Teaching Method that Activates High Levels of Bloom’s Taxonomy**

Using data grouped by teaching method, cumulative linked mixed models were generated to produce heat maps displaying the effect size between levels of Bloom’s Taxonomy, as well as the *p* values indicating the significance of each effect size (Figs. 5, 6). These models utilize the same data shown in Figs. 3 and 4 and encompass domains of mass conservation and kinetics, respectively. For the mass conservation model, significant effects were found for Bloom’s level (*χ^2 (5) = 91.5, *p* < 0.001), teaching method (*χ^2 (3) =

![Heat maps indicating the effect size between levels of Bloom’s Taxonomy for four teaching methods, as reported by students for mass conservation. Effect size is shown as color and is calculated as the predicted mean of the level on the y-axis minus that on the x-axis, divided by the standard error of difference. Asterisks indicate the p value of the post-hoc test between different level pairs (*p* < 0.05, **p** < 0.01, ***p*** < 0.001). Note that the maps are symmetric over the diagonal, although with an opposite sign.](image-url)
110.8, \( p < 0.001 \), and their interaction (\( \chi^2 (15) = 428.6, p < 0.001 \)). No significant effect of year was observed (\( \chi^2 (1) = 3.46, p = 0.063 \)). For the model fitted with kinetics data, each of Bloom’s level (\( \chi^2 (5) = 164.8, p < 0.001 \)), teaching method (\( \chi^2 (3) = 113.3, p < 0.001 \)), and their interaction (\( \chi^2 (15) = 141.6, p < 0.001 \)) were again found to be significant factors, in addition to year (\( \chi^2 (1) = 4.82, p = 0.028 \)). The statistical results from these models indicate a complex relationship between teaching method and Bloom’s level. The intricacies of this relationship are elucidated through observing the mean differences and post-hoc testing between levels of Bloom’s Taxonomy (Figs. 5, 6).

Positive differences, indicated by red, identify pairs in which students reported higher activation scores for the level on the y-axis than the level on the x-axis. Conversely, negative differences, indicated by blue, identify pairs in which students reported lower activation scores for the level on the y-axis than the level on the x-axis. Thus, it is evident that for lecture in the mass conservation domain (Fig. 5a), Remember and Understand had scores that were significantly higher than scores for Apply, Analyze, Evaluate, and Create. Additionally, Create is uniquely distinct from the lower five levels of Bloom’s Taxonomy. These statistical models support the findings from Fig. 3 indicating lecture is a task that readily supports objectives at lower levels of Bloom’s Taxonomy for mass conservation topics. Similarly, homework and in-class problems (Figs. 5b and 5c) in the mass conservation domain appear to distinguish statistically between the lower four levels (Remember, Understand, Apply, and Analyze) and the upper two levels (Evaluate and Create). There is also evidence that students view homework and in-class problems as being more beneficial to the middle levels of Bloom’s Taxonomy (Apply and Analyze) compared to lecture. Again, Create is statistically distinct from the lower five levels, indicating students do not perceive lecture, in-class problems, and home-
work as enabling them to reach the highest level of Bloom’s Taxonomy. The results for PBL within mass conservation are opposite to that of lecture, in that Remember and Understand have significantly lower reported scores than those for the higher four levels; this finding identifies PBL (Fig. 5d) as a teaching method that not only exclusively supports high levels of Bloom’s Taxonomy, but also provides additional support for the middle levels.

Similar results are observed in the kinetics domain in Fig. 6. In lecture, the lowest two levels of Bloom’s Taxonomy are reported with significantly higher scores than the highest four levels (Fig. 6a). For in-class problems and homework (Figs. 6b and 6c), the lowest four levels are statistically distinct from the highest two levels. Create is once again statistically distinguished from the lower five levels for in-class problems and homework, and the lowest four levels in lecture. However, a slightly reduced effect is seen for PBL (Fig. 6d). Though Remember and Understand appear to be distinguished from Apply, Analyze, and Create, no significant difference is seen between the lower two levels and Evaluate, which is the second highest level. Additionally, Evaluate is not seen as significantly different from any of the other five levels. Regardless, these findings suggest three of the four highest levels of Bloom’s Taxonomy are still supported by PBL, providing further evidence that PBL provides a learning experience more specific to higher levels of Bloom’s Taxonomy and distinguishes itself from lecture, in-class problems, and homework; these statistical models support findings from Fig. 4.

Overall, the data shown in Figs. 3, 4, 5 and 6 suggest students identify:

- Lecture as a teaching method that most readily supports attaining education goals at lower levels of Bloom’s Taxonomy, specifically Remember and Understand.
- Homework and in-class problems as teaching methods that most readily support middle levels of Bloom’s Taxonomy, specifically Apply, as well as Analyze and Understand to a lesser extent.
- PBL as a teaching method that exclusively supports high levels of Bloom’s Taxonomy, specifically Create and Evaluate, as well as readily supports middle levels of Bloom’s Taxonomy, including Apply and Analyze.

Time Spent in PBL Corresponds to Increases in Skill and Confidence

At the end of the semester, students report their extent of their preparedness, need for practice, increase in confidence as a biomedical engineer, increase in skill or ability, and time spent on 14 separate tasks in Table 3 (nine technical tasks and five professional tasks). Fig. 7a shows students’ perceived increase in skill as a function of their time spent in a variety of class tasks, grouped by taxonomic level.

Though there is a distribution of times spent and degrees to which skill were increased, on average, high-level tasks (shown in blue) and middle-level tasks (shown in yellow) score higher in both time spent and perceived increase in skill than low-level tasks (shown in red) (Fig. 7a). This overall pattern is extended when comparing increases in confidence with time spent in Fig. 7b, where students also report increases in confidence with high-level tasks compared to low-level tasks. Fig. 7c shows the perceived skill increase as a function of the perceived confidence increase, where there is also a noticeable difference between low- and high-level tasks. The proximity of the average data points to the line of unity, shown with the black line, on Fig. 7c indicates the two attitudes are closely related ($R^2 = 0.68$, calculated over all individual student responses).

The statistical significance of these trends was calculated using a two-factor ANOVA with the survey prompts (increase in confidence, increase in skill, and time spent) and level of Bloom’s Taxonomy (low, middle, and high) as the treatments. It was found that significant variation was due to the levels of Bloom’s Taxonomy ($p < 0.001$), but the variation due to the survey prompts and the interaction terms were not significant ($p = 0.142$ and 0.317, respectively). Post-hoc testing revealed a significant difference between the reported scores for low and middle levels of Bloom’s Taxonomy, as well as those for low and high levels ($p < 0.001$ for both). The middle and high levels were not significantly different ($p = 0.317$). These results indicate that students view low-level tasks differently from middle- and high-level tasks in a PBL setting.

These differences can be further specified with a series of one-factor ANOVA and post-hoc testing for each of the individual prompts (increased confidence, increase skill, and time spent). Table 4 shows the $p$ values for the various pairs of post-hoc tests, grouped by prompt. Once again, significant differences are observed between low and middle levels, as well as low and high levels. However, no significant difference is seen between middle and high levels for any of the three prompts. These results indicate that students consistently perceive their time spent in PBL as being on middle- and high-level tasks compared to low-level tasks. This is consistent with the assertion that PBL requires tasks that are high on Bloom’s Taxonomy. These data support the intended outcomes of the course structure, in which a sizeable portion of the
workload is allocated to PBL to address high levels of Bloom’s Taxonomy.

In summary, these responses indicate students consistently perceive their time spent in PBL as being more invested in high-level tasks compared to low-level tasks. This is consistent with the assertion that PBL requires completing tasks that are high on Bloom’s Taxonomy. Higher reported scores for increases in skill and confidence are associated with increased time spent in middle- and high-level tasks. These data support the intended outcomes of the course structure, in

| Pairs of Bloom’s Taxonomy level | Increased confidence | Increased skill | Time spent |
|---------------------------------|----------------------|----------------|------------|
| Low/middle                      | 0.029                | 0.093          | < 0.001    |
| Low/high                        | < 0.001              | < 0.001        | < 0.001    |
| Middle/high                     | 0.585                | 0.152          | 1.000      |

FIGURE 7. Students’ attitudes regarding class tasks. (a) increased skill vs. time spent; (b) increased confidence vs. time spent, (c) increased skill vs. increased confidence. Error bars indicate standard deviation over all students. Colors indicate taxonomic level (red = low, yellow = middle, blue = high), with light coloring indicating individual tasks and dark coloring indicating the mean score over the level.

TABLE 4. $p$ values for post-hoc testing of pairs of Bloom’s Taxonomy levels for different survey prompts.
which a sizeable portion of the workload is allocated to PBL to address high levels of Bloom’s Taxonomy.

Students’ Perception of Preparedness and Practice for Professional Tasks Changes with Exposure

At the start and end of the semester in spring 2020, students report their extent of their preparedness and need for practice on the 14 tasks in Table 3. The reported scores for four professional tasks (oral presentations, writing, teamwork, and project planning) are compared. Fig. 8 shows students’ perceived need for more practice plotted as a function of their perceived preparedness at the start of the semester. Data are indicated by marker type, for pre-class (shown in blue) and post-class (shown in red) responses.

Although there is a range of perceived need for practice and preparedness levels in both the pre-class and post-class surveys, on average, students reported a statistically significant greater need for practice and a lower preparedness level at the end of the semester \( (p = 0.037 \text{ and } p < 0.001, \text{ respectively}) \). The mean reported score over all students and professional skills suggests students overestimate their preparedness and underestimate the degree of practice they require. These shifts in attitudes may reflect a change in their understanding of the complexity of these tasks. As students find greater exposure to these professional tasks, they may find that their experiences prior to this course were insufficient, and they, in fact, have much more to learn and practice.

Students’ Feedback Indicates Utility of PBL

Table 5 lists the five largest categories of student responses to the prompt, “List the 1 to 2 things you hope to learn/improve in the PBL projects,” as well as all other coded categories grouped into an “other” category. Category size is determined by the percent of total coded responses and is noted in the second column. Bloom’s level is presented as defined in Table 3.

Two of the largest categories (creating models/equations, simplifying complex systems) are high-level tasks, suggesting many students have an expectation they will engage in creation and evaluation, the two highest levels of Bloom’s Taxonomy. In particular, the largest category (creating models/equations) is a substantial plurality of responses, with over 7% more than the second largest category and 3% more than the “other” category. The other largest categories are research and finding numbers, teamwork, and written/oral presentations. Research and finding numbers are classified as middle-level tasks; teamwork and presentations are professional skills.

![FIGURE 8. Students’ attitudes regarding professional tasks. Need for practice plotted as a function of preparedness at start for four different professional tasks, with colors indicating data from the pre-class survey (blue) and post-class survey (red). Marker style indicates task, with light coloring indicating individual tasks and dark coloring indicating the mean score over all tasks. Error bars indicate standard deviation over all students.](image-url)
**TABLE 5.** Frequency of responses as percent of total coded responses regarding material students hope to learn, with selected examples.

| Category                        | %     | Selected Examples                                                                 | Bloom’s level |
|---------------------------------|-------|----------------------------------------------------------------------------------|---------------|
| Creating models/equations       | 25.8  | “I hope to learn how to make models and to apply equations to complex problems”   | High          |
| Research and finding numbers    | 18.3  | “How to effectively read literature papers to understand what the research was about and to be able to quickly identify key statistics” | Middle        |
| Simplifying complex systems     | 14.0  | “I would like to learn how to effectively model systems that are simplified yet still quite accurate [sic] reflect reality” | High          |
| Teamwork                        | 10.8  | “Become a better group leader and work with different types of people”            | Professional  |
| Written/oral presentations      | 9.7   | “I hope to improve my ability to write and orally present effectively, especially since I hope to be a doctor where both of these skills will be very important” | Professional  |
| Other                           | 21.2  |                                                                                  |               |

**TABLE 6.** Frequency of responses as percent of total coded responses regarding anticipated challenges of the course, with selected examples.

| Category                        | %     | Selected Examples                                                                 | Bloom’s level |
|---------------------------------|-------|----------------------------------------------------------------------------------|---------------|
| Teamwork                        | 26.2  | “Dividing work so it can be put together in modular fashion. Communication with team members” | Professional  |
| Research and finding numbers    | 18.4  | “Finding information that is specific enough for our project within the given time frame” | Middle        |
| Creating models/equations       | 16.3  | “Mathematical modeling—finding a relationship between components will be a challenging part of our project” | High          |
| Simplifying complex systems     | 13.5  | “Making models too complicated and not knowing what to cut down”                   | High          |
| Project planning                | 10.6  | “Pacing ourselves throughout the duration of the project because there are no explicit checkpoints along the way” | Professional  |
| Other                           | 14.9  |                                                                                  |               |

**TABLE 7.** Frequency of responses as percent of total coded responses regarding most rewarding aspects of the course, with selected examples.

| Category                        | %     | Selected Examples                                                                 | Bloom’s level |
|---------------------------------|-------|----------------------------------------------------------------------------------|---------------|
| Accomplishment of achieving final product | 22.1  | “I also think handing in the physical report with all of our figures, code, and appendices was a very satisfying feeling. It was nice to see how much we had accomplished in just a few weeks” | N/A           |
| Teamwork                        | 17.3  | “By far my favorite part of PBL was my team itself. We had a good group that meshed well together” | Professional  |
| Creating working models         | 15.4  | “Developing a model that I felt was accurate and clinically relevant”             | High          |
| Real-life applications          | 10.6  | “Having a real-life application of what we are learning in class that we actually create (it feels very realistic and closer to what actual engineers do than other projects)” | N/A           |
| Recognition of confidence and personal growth | 8.7   | “It was a sense of accomplishment and increased my confidence in being able to solve more complex, open-ended problems in the real world” | N/A           |
| Other                           | 25.8  |                                                                                  |               |
Table 6 lists students’ responses to “List the 3 to 4 challenges you anticipate in the PBL projects,” where again, creating models/equations and simplifying complex problems are featured. Many responses indicate that teamwork as well as research and finding numbers would be a challenge, which mirrors the skills they hope to learn in Table 5. Project planning is the fifth most common response. Note that students anticipate challenges in middle- and high-level tasks as well as professional skills.

Table 7 lists responses to “List the 1 to 2 most rewarding aspects about the PBL projects.” Continuing a trend observed in Tables 5 and 6, creating models and equations is one of the most common responses. The most common response, however, is a feeling of accomplishment related to the final product. A related sentiment, a recognition of confidence and personal growth, is the fifth most common response. Other common responses are teamwork and the real-life applications of course material. Note that three of these categories were coder-generated through the process described in the Methods. Note that not all categories in Tables 7 and 8 are assigned a Bloom’s level.

Lastly, Table 8 lists responses to “List the 3 to 4 most frustrating things about the PBL projects.” Recalling anticipated frustrations in Table 6, researching and finding numbers prove to match students’ expectations as one of the more frustrating elements. Students again note creating models and equations as one of the most common responses, although it ranks fifth. Though students report teamwork as one of the most common rewarding aspects, teamwork is also reported as the top-ranked most common frustrating aspect. Other listed frustrations are the lack of clear feedback/facilitation and the course workload. The lack of clear feedback/facilitation might be due to some less experienced TAs. However, this might also be due to students’ misunderstanding that the team (not the instructor or TA) should be driving the model creation, or this might be due to the difficulty students experience in transition between teaching methods.

The student responses in Tables 5, 6, 7, and 8 indicate a strong, overarching trend: though creating models is expected to be and eventually perceived as a frustrating, challenging task, it is also rewarding and addresses the most popular course objective. Note that the most frequent category of responses on any question is often above 20% of all coded responses and sometimes a plurality of responses when “other” is treated as a stand-alone category. Additionally, professional skills such as teamwork emerge as challenging but desirable and rewarding skills for students to develop over the course of PBL. Absent from the most popular categories are lower-level skills, such as understanding biology. Retrospective responses in Tables 7 and 8 indicate additional benefits to and practical considerations for implementing PBL; these will be discussed in the next section.

### DISCUSSION

**Activation of Different Levels of Bloom’s Taxonomy Using Diverse Teaching Methods**

Students report that different teaching methods and classwork types are more or less effective for helping them achieve different levels of Bloom’s Taxonomy. Moving from lecture to PBL in Figs. 3 and 4, the

| TABLE 8. Frequency of responses as percent of total coded responses regarding most frustrating aspects of the course, with selected examples. |
|---------------------------------------------------------------|
| Category | % | Selected Examples | Bloom’s level |
|----------|---|--------------------|---------------|
| Teamwork | 14.3 | “Working with six other people is difficult to keep everyone accountable and working as efficiently as possible” | Professional |
| Clearer feedback/facilitation | 12.4 | “A frustrating thing overall would be that the mentors gave varying levels of helpful feedback. In other words, some were really helpful and made sure to check in with the team on their progress while others did not really pay attention during the PBL meetings” | N/A |
| Research and finding numbers | 11.8 | “The most frustrating pieces were likely finding numbers and assembling sources (since we had difficulty keeping track).” | Middle |
| Workload | 9.9 | “It was difficult to dedicate the appropriate amount of time to the PBL projects when we all have very full schedules. I wish I could have had more time to dedicate to PBL” | N/A |
| Creating models/equations | 7.5 | “For creating a model, there is not necessarily one “right” answer, but many correct answers that fit into the project guidelines. This could be frustrating at times when we did not know if we were on the right track” | High |
| Other | 44.0 | | |
reported activation score for high levels of Bloom’s 
Taxonomy increases. This effect is more visible for 
mass conservation, though it is still present in kinetics. 
These results suggest that students recognize that 
specific teaching methods may be better aligned with 
improving their learning at particular levels of Bloom’s 
Taxonomy.

The diverse teaching methods in BME 260 allow 
each level of Bloom’s Taxonomy to be targeted, 
ensuring that students build foundational knowledge 
while also having space to synthesize ideas and create 
mathematical models. The output of the cumulative 
linked mixed model adds quantitative support for the 
visual trends seen across teaching methods. In the 
models, a statistically significant difference is seen 
between the lowest levels of Bloom’s Taxonomy ( 
Remember and Understand) and the highest levels 
(Evaluate and Create) in lecture and PBL. Additionally, 
lecture appears to distinguish the lowest levels 
from the middle levels (Apply and Analyze), further 
suggesting that lecture is best suited for Remember and 
Understand. In-class problems and homework appear 
to distinguish only the highest levels of Bloom’s Tax-
onomy from the lower four levels, which suggests there 
is expanded support for the middle levels. Overall, the 
statistical findings from lecture, in-class problems, and 
homework indicate that none of the traditional 
teaching methods activate high levels of Bloom’s Tax-
onomy in a significant fashion. Conversely, PBL 
was found to be the only teaching method to activate 
high levels. With regard to Research Question 1A, the 
cumulative linked mixed model shows that students 
recognize that different teaching methods develop their 
skills at different levels of Bloom’s taxonomy to a 
statistically significant extent. Regarding Research 
Question 1B, the model indicates that high levels of 
Bloom’s taxonomy are not realized with traditional 
teaching methods such as lecture and homework.

These statistical conclusions borne from the cumu-
lative linked mixed model aligns with the findings in 
one of the most comprehensive meta-analyses of PBL 
assessment. Gijbels et al. found that PBL has a robust 
effect on increasing students’ application of skills, but 
a slight negative effect for simply acquiring knowledge 
and information. However, in the present case of 
BME 260, the medley of teaching methods af-
fords students opportunities to solidify lower taxo-
nomic level knowledge as well as challenge students at 
higher taxonomic levels. Clyne and Billiar’s work in 
biomedical engineering similarly explores their multi-
faceted course and how different teaching methods 
align with different levels of Bloom’s Taxonomy. The 
authors confirm that the integration of traditional 
teaching methods with PBL harmonizes well: students 
reported that homework assignments were helpful in 
clarifying how the theory could be applied to open-
ended problem prompts, including analyzing experi-
mental data and developing a model for a prosthetic 
limb.

Impact of PBL on Student Self-efficacy

A major outcome of PBL is a sense of self-efficacy 
instilled by tackling and proposing solutions to these 
complex problems. The surveys used in this study 
did not directly measure self-efficacy through a vali-
dated survey but rather had students reflect on 
increases in skills and confidence in particular areas 
relevant to the course. The most direct measure of self-
efficacy is shown in Fig. 7, where the triplet responses 
of time spent, increased skill, and increased confidence 
appear well-aligned. More time is spent on high-level 
tasks, which are emphasized in PBL, compared to low-
level tasks, and a corresponding statistically significant 
increase in skill and confidence is observed. Fur-
thermore, the increase in skill is nearly matched to the 
increase in confidence (Fig. 7c), suggesting students 
view these as closely related. Similar results are 
observed comparing middle-level tasks to low-level 
tasks.

The qualitative responses regarding the rewarding 
aspects of PBL (Table 7) support the idea that PBL 
improves students’ self-efficacy. The most common 
response category was a feeling of accomplishment 
related to completing the final product, which com-
prised 22% of coded responses. These responses indi-
cate that students feel like they had accomplished a 
significant and difficult task, as shown by the example 
quote. Another popular category was creating working 
models, in which students expressed a rewarding feel-
ing related to having a mathematical model that was 
accurate and true to their understanding of the biol-
ogy. Again, these attitudes support the idea that stu-
dents derive satisfaction from an accurate and 
complete model, as described in previous studies on 
PBL. The fifth-most common category was an exp-
licit mention of recognition of confidence and per-
sonal growth, where students directly mentioned 
advances in their confidence to approach and solve 
complex, open-ended problems. Regarding frustrating 
aspects of PBL (Table 8), no students indicated a loss 
of confidence in their abilities, but focused instead on 
course aspects that could be improved to increase their 
learning and confidence, such as improvements to 
instructor facilitation and feedback.

The combined quantitative and qualitative analysis 
shows that students report statistically significant 
increases in skill and confidence with more time on 
task. Furthermore, students report greater increases in 
skill and confidence for high-level tasks compared to
low-level tasks. These results support Research Questions 2A and 2B. These data reflect the expected benefits from PBL from several recent studies in building students’ self-efficacy.17,20,27,44 It is also supported by early findings from cognitive apprenticeship and constructivism.14 When students are given support while carrying out high-level tasks, they build confidence in their abilities. In PBL, though this support often comes from instructors and TAs, there is space for it to come from peers. A study in cooperative learning styles by Levin corroborates the findings of PBL and other group-based, high-level work, where students find the task of pooling knowledge and capabilities to produce high-quality work beneficial to their self-confidence.41 Bilgin et al. found that PBL paired with an emphasis on cooperative learning not only increased students’ academic performance and reported enjoyment of the course, but also decreased negative attitudes towards the course, such as fear and nervousness.9

Professional Skills Developed Through PBL

An additional outcome of PBL is the development of key professional skills. Though the authors do not directly tie these skills to levels of Bloom’s Taxonomy, professional skills are demanding and complex tasks.36 Additionally, these skills are critical to success beyond the classroom environment but are not always explicitly practiced or taught. A comparison between students’ responses before and after the course reveals that the perceived degree of preparation at the start of the course decreases for all four professional skills queried (Fig. 8). This decrease suggests students were slightly overconfident in their ability in professional tasks at the start of the course and this attitude was adjusted over the semester. Overconfidence in professional skills has been noted in other studies.39,47 This overconfidence may arise from a lack of exposure to these types of tasks in the curriculum prior to BME 260. For example, students have had one or two engineering classes where teamwork and project planning were central tenets. The increase in scores across the semester for needing more practice corroborates this idea. When students have more exposure to particular professional skills, they become more aware of the complexities and difficulties of these types of tasks. Thus, students may recognize they need more practice than previously thought to address deficiencies in their professional skills. Students also indicated that practicing these skills was rewarding; teamwork is the second most common response in Table 7 and additional students quotes (not shown) reveal that practicing oral and written communication skills was satisfying and helpful. This finding mirrors previous work that describes students’ attitude towards team-

Work that describes students’ attitude towards teamsatisfying and helpful. This finding mirrors previous student quotes (not shown) reveal that practicing these skills was rewarding; teamwork is the second most common response in Table 7 and additional students quotes (not shown) reveal that practicing oral and written communication skills was satisfying and helpful. This finding mirrors previous work that describes students’ attitude towards team-

Strengths of the Current Study

The present study has several notable strengths compared to previous work on PBL education in biomedical engineering. First, while BME 260 is a hybrid lecture/PBL course, this study asks students to disentangle the effects of PBL from other teaching methods. Compared to the few previous publications that examine PBL distinctly compared to other teaching methods, this study adds internal validity by controlling for subject topic in the lecture and PBL teaching methods, rather than teaching different topics through the different teaching methods.77 In addition to separating PBL from other classwork types when asking students to reflect, asking students to report on the efficacy of each pairwise combination of teaching method and Bloom’s Taxonomy level allows for a nuanced look at the effect of each method. Previous work by Mitchell et al. found modest increases in students’ understanding of various topics following an entirely PBL course.46 Our work expands upon these findings by asking students to independently consider each of several teaching methods, which isolates the effect of each teaching method on the mastery of individual Bloom’s Taxonomy levels.

Second, the within-subject design controls for differences between class cohorts. While between-subject designs have been used in studies comparing students in PBL to a separate control cohort enrolled in traditional courses, the results of these studies could be influenced by many other variables that affect students’ learning over the course of a semester or program.9,75 The status of BME 260 as a required course also helps control for cohort differences. If students had the choice to opt in to a PBL course or remain in a traditional one, findings on the efficacy of PBL and student satisfaction may be skewed, as data would only come from those who consciously chose to learn via PBL. The present study adds external validity to the literature by controlling for student interest in PBL.

Limitations of the Current Study and Recommendations for Future Work

Our study is limited by several factors, which also guides specific recommendations for future researchers. First, the use of student self-reporting to measure the efficacy of teaching methods on each level of Bloom’s Taxonomy allows for limited inference regarding actual student achievement of learning outcomes at the various levels. While perception of mastery usually aligns with having mastered a topic,
students may still fail to accurately report their skills and competencies and its link to a particular teaching method.\textsuperscript{2,29} A related limitation is that students within a PBL team may share tasks in a way that some students preferentially develop some skills over others. A future line of work would be to use open-ended assessments to obtain direct information on students’ learning and competencies at different Bloom’s Taxonomy levels.\textsuperscript{77} Another strategy would be to reconsider the overall study design, such as using an A–B–A–B approach, to measure the impact of the different teaching methods within individual students, where the repetition of the treatment blocks allows for maximal power.\textsuperscript{77}

A second limitation is that the administered survey asked students to rate their confidence on certain topics, which we are using as a proxy for self-efficacy. The use of a validated scale, such as the General Perceived Self-Efficacy Scale, would add validity to findings and is a robust way to measure students’ perceptions.\textsuperscript{20,43,45} As is common with course surveys, open-ended questions were useful in obtaining themes to guide the analysis. In future work, these new themes could be explored further using specific probes and questions. Replies to open-ended questions also helped to improve specific aspects of the course such as deadlines, weighting of assignments, and a more comprehensive introduction to PBL.

Third, more years of student data could also be captured. In addition to bolstering the assumptions required for a cumulative linked mixed model, continued trends with a greater sample size would lend external validity to the present findings. However, cohort effects must be taken into consideration with more years of student data.

Finally, future work can build off the present findings by attempting to validate the above mapping of teaching methods and specific tasks to the levels of Bloom’s Taxonomy. The instructor acknowledges that her choice of specific questions and prompts within particular teaching methods may have directly affected the student’s perceived Bloom’s level. While different choices of tasks could have been made (e.g., very open-ended, Create-focused questions for homework vs standard plug-and-chug homework problems from the textbook), these pairings of teaching methods and Bloom’s level are typical for many STEM courses.\textsuperscript{31,63} Additionally, researchers could ask students if they perceive each teaching method to be effective. The ultimate goal would be a refined, enhanced Bloom’s Taxonomy for BME 260, with course tasks added to each level to ground the theory in work for students. By asking students to consider Bloom’s Taxonomy in a more concrete way during the learning process, we hope to activate metacognitive reflection on how effective each teaching method is for learning, and thus maximize students’ growth through the various aspects of the course.\textsuperscript{56,70}

**Application to Practice**

The authors assert that students in undergraduate biomedical engineering programs need to routinely practice skills at all levels of Bloom’s Taxonomy. In other words, first-year through senior students should be expected to Analyze, Evaluate, and Create. Interestingly, students recognize that the regular lecture, homework, and even active learning in-class problems really hit no higher than Apply. Recognizing a problem and applying the correct equation are important and necessary skills, but they are not sufficient for developing engineers to confront complicated challenges of the future.\textsuperscript{34,48} Historically, work at high levels of Bloom’s Taxonomy has been saved for open-ended capstone design projects. This work demonstrated that PBL is a teaching method recognized by both students and instructors for achieving high levels of Bloom’s Taxonomy, and that PBL is a teaching method that has the potential to be integrated into courses across the biomedical engineering curriculum to achieve learning at high levels of Bloom’s Taxonomy.

In this course, PBL was used as one of many teaching methods. While PBL can be used alone and there are merits to this approach,\textsuperscript{50} this work demonstrates that PBL can also be integrated as a significant component in a typical analytical engineering course. With this instructional model, students learn the equations describing the conversation of mass and energy, as well as basic kinetics; the application of these equations to traditional closed-ended problems; and how these equations can mathematically model complex biological systems. By requiring students to write a technical report and give an oral presentation, students also developed their communication skills. Rubrics assist in comparing the quality of different teams’ work and allow for direct and specific feedback, as well as provide a framework for expectations for quality and content.

The implementation of PBL requires effort on the part of the instructor, and the instructor must be comfortable facilitating students in solving problems without known answers. TAs and instructors need to be skilled at providing appropriate and timely feedback to student teams, as well as managing difficult teams and/or team members. Class time historically used for lecture or similar didactic strategies must be reduced to make room for PBL, as simply assigning an out-of-class project does not provide the scaffolding necessary for a successful implementation of PBL.\textsuperscript{46} Specifically, the instructor needs to offer guidance and
examples to help students learn to simplify highly complex systems, make valid assumptions, research and find key information in an overwhelming volume of biomedical literature, and stay on track with their projects. In addition, instructors must actively coach and encourage students to solve problems across different scales and complexities. While there may be some initial resistance to working on such open-ended PBL prompts alongside learning new technical material, many students recognize the benefits of this approach. Overall, the integration of several teaching methods including PBL into BME 260 has resulted in a challenging class designed to support students’ intellectual and professional growth as biomedical engineers.

CONCLUSION

PBL, which engages students in open-ended real-world problems, has grown in popularity among post-secondary educators, particularly in STEM fields. Previous work has found a positive impact of PBL on activating higher levels of learning compared to traditional lecture. The present work corroborates this body of literature with quantitative and qualitative assessments of students’ reported experiences in an undergraduate biomedical engineering course that uses a mixture of traditional teaching methods and PBL. Using the six levels of Bloom’s Taxonomy as a framework, surveys ask students to consider each teaching method separately when reflecting on learning. This work provides strong evidence that PBL most successfully achieves learning at higher levels of Bloom’s Taxonomy, with support for its effect on learning at middle levels of Bloom’s Taxonomy. Additionally, this work identifies that students do not perceive lecture and homework as activating learning at higher levels of Bloom’s Taxonomy. Students also reported increases in their skills and confidence, with more time spent on high-level tasks compared to low-level tasks. This central claim is bolstered by linking PBL and higher-level thinking with students’ analysis of various course tasks and a presentation of open-ended survey responses; salient themes from the latter motivate a discussion of the practicalities of PBL. While there are challenges associated with PBL’s implementation, students’ robust feedback in support of PBL and several practical suggestions for implementing PBL are offered to motivate more instructors to adopt PBL in the biomedical engineering curriculum.
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