2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #40188

A Generative Learning Approach to Teaching Engineering Calculations in an Introductory Course

Dr. Kathryn R. Gosselin, State University of New York, Maritime College

Kathryn R. Gosselin is a Senior Assistant Professor in the Mechanical & Facilities Engineering Department at SUNY Maritime College. She has a Ph.D. in Mechanical Engineering from the University of Connecticut. She joined Maritime College in 2018 and teaches upper-division courses in the thermofluids area. Additionally, she is Coordinator of Advising for the School of Engineering and is involved in assessment.

Dr. Martin S. Lawless, State University of New York, Maritime College

Martin Lawless is currently an Assistant Professor of Mechanical Engineering at SUNY Maritime College. He earned his Ph.D. in Acoustics in 2018 from the Pennsylvania State University where he investigated the brain/s auditory and reward responses to room acoustics. Martin's current research involves the perception of sound in virtual environments, low-cost measurement devices, and engineering education.

A generative learning approach to teaching engineering calculations in an introductory course

Abstract

In many introductory engineering courses, the fundamentals of documenting engineering calculations serve as an important learning outcome for the first-year students. Specifically, students are instructed on how to properly format an engineering calculation from writing a straightforward analysis on engineering graphing paper to assigning unique variable names to relevant physical quantities, among other concepts. In a large (100-150 students) first-year course at a public university, this topic had previously been taught via a traditional lecture method. In this traditional approach, expectations are first described to the students and then briefly demonstrated in several examples, and students are provided a written guide of the rules. This paper examines a new approach, in which students are instead provided with a problem statement accompanied by three instructor-generated solutions to that problem. The three solutions arrive at the same correct numerical answer, but contain varying levels of detail and clarity. Students were asked to identify the specific differences among the solutions and explain what made one solution more clear and complete than another. As a class, the students developed the list of rules for engineering calculations based on their observations. Student performance on an engineering calculation homework assignment was compared between two semesters that each used the traditional approach and the new approach, respectively, to determine if the students fared better with one approach over the other. The results showed a greater variation between graders within each semester. than between instructional approaches, and future work is proposed to improve the consistency of grading.

Introduction

Despite the increasing prevalence and necessity of computational solutions to engineering problems, as well as the successful adoption of web-based systems for homework delivery and automated grading in engineering courses [1, 2, 3], hand calculations remain indispensable in engineering education and practice. Calculations by hand are frequently used in academia to support and validate numerical solutions, as well as assess students more thoroughly on examinations, since most web-based solutions are only able to assess the numerical answer, not the process the student utilized to get there. In engineering practice, clear documentation is essential for allowing checking and certification of design calculations.

In order to standardize the presentation of engineering calculations, some industry groups and government agencies prescribe a standard format, such as those by the Energy Facilities Contractors Group [4] and the Hanford Site's instructions for contractors [5]. Similarly, it is typical for engineering students to be instructed on a recommended format for their calculations, and some institutions even standardize the required format across a program, department, or school, such as in the University of Missouri College of Engineering [6] or the Auburn University Department of Chemical Engineering [7]. These formats generally recommend or require certain sections (such as the problem statement or the design statement), describe the appropriate level of detail for analytical and numerical calculations, require the use of scientific or engineering format for numbers, and advise that units should be listed throughout.

Adhering to a clear and consistent calculation format serves a number of practical purposes. The student can more easily check calculation which are neatly presented, and they can return to the calculations later for studying purposes. The instructor can review the students' calculations more quickly and spot errors easily, facilitating prompt feedback, which has been shown to be essential to the effectiveness of formative assessment. Additionally, Taraban *et al.* found that written solutions to undergraduate statics practice problems can contain some useful information about the students' comprehension of the material, particularly related to the construction of free-body diagrams and equation expansions [8], so instructors may be able to gather data on overall student comprehension. Despite the ubiquity of engineering calculations and standard formats thereof, there is little previous work studying instructional techniques specifically related to documentation of calculations.

One such technique that could potentially be beneficial to engineering calculation outcomes is generative learning. First named by Osborne and Wittrock in the early 1980's, generative learning proposes that science learning is improved by asking students to construct their own mental maps of new information and synthesize it with previous knowledge [9, 10]. This technique includes a wide range of exercises, including summarizing, making concept maps, drawing, self-testing, self-explaining, and teaching [11], all of which have been shown to improve student performance to varying degrees [12]. A recent meta-analysis analyzed the relative effectiveness across different age groups of a number of common generative learning strategies and found that college students were the group for whom all the studied strategies were most consistently effective, and that results were mixed or even negative among younger students [13].

Formal study of the application of generative learning to engineering education is somewhat sparse, though several specific generative activities have shown promise. In one such case, students in a computational science course were given extra credit for including self-explanation of worked examples via comments in the code. The authors found that high performers were more likely to connect their explanations to laws and principles, whereas low performers were more likely to superficially describe code features [14]. Similarly, students in an introductory-level electrical engineering who were specifically instructed on drawing and prompted to do so when problem-solving scored slightly better on tests of conceptual understanding than those who were not [15].

In the present study, a generative learning technique was applied to the instruction of engineering calculation formatting. Students participated in a self-explanation activity in which they compared the positive and negative aspects of several different hand calculations, and then were assessed on their own hand calculations with a homework assignment. To ascertain whether the students benefitted from the generative learning method, overall performance on the assignment was compared with that of a similar homework assignment in a previous semester in which a more traditional lecture method was used.

Instructional Methods

At the State University of New York Maritime College, all students in the five engineering programs (Mechanical Engineering, Facilities Engineering, Electrical Engineering, Naval Architecture, and Marine Engineering) are required to take an introductory first-year course, ENGR 110: Introduction to Engineering Practice. The School of Engineering has a prescribed calculation format which is taught in this class and required in all courses within the School. Students are required to complete calculations on engineering paper and include a heading on each page with relevant information such as the student's name, the course, the assignment, and the page numbering. The body of the calculations must include a problem statement, a sketch when appropriate, a step-by-step calculation utilizing unique variables for all values and requiring that all calculations be represented symbolically first, and a numerical answer with units. Anecdotally, many students struggle to adopt this approach, particularly the requirements related to symbolic representation of variables and equations. Instructors in upper-division courses often have to spend additional time reviewing the required format and grading assignments whose calculations are difficult to follow.

To lessen the burden on core major instructors, Introduction to Engineering Practice includes instruction on the format, as well as one or more assessments (homework, plus an examination in some semesters). The assignments have generally been simply geometric calculations requiring only standard high school math, such that students are being assessed primarily on their ability to document their calculation steps. In the past, however, instructors felt that the results were mixed, with many students still struggling to understand the purpose of the format and implement it in their calculations.

In an attempt to improve student implementation of the required format, the authors significantly changed the instructional technique in a recent year from a traditional lecture format in which the instructor described and demonstrated the required format to a self-explanation activity in which students studied examples of engineering calculations, analyzed them, and formulated guidelines based on their observations.

In fall 2021, a traditional lecture was used to deliver the material. Due to the size of the course and concerns about COVID-19, the lectures were delivered virtually, but the content was identical to previous semesters. The instructor showed the students slides which outlined the required calculation steps, showed some standards of mathematical calculations, and then showed several examples. Students were also provided with a written document which outlined the same requirements in detail and included a written example.

In fall 2022, the same material was delivered in a new way. Rather than directly explaining the required calculation steps, the instructor provided three examples of written solutions to the same problem with varying levels of detail and clarity. The three solutions were created by the instructor and specifically designed to incorporate common student errors in calculations. All three solutions reached the same correct answer, but documented it with varying degrees of clarity and consistency. The first example followed the calculation format expectations precisely (the "A" solution), including defining and using unique variable names, showing all algebraic operations, and providing a problem statement and well-labeled sketch. The second example was relatively clear (the "C" solution) but contained a number of common documentation errors, including neglecting to define all variables clearly, repeating variable names to represent distinct quantities, and doing calculations numerically rather than symbolically. The final example was an extremely brief numerical calculation without any definition of the problem, the variables, or the process (the "F" solution). Students were asked to rank the solutions in terms of overall quality and to list differences between the solutions. First, they compared the A and F solutions, which allowed students to see the obvious benefits of the required format. Next, they compared the A and C solutions, which was intended to show them the more subtle differences between a solution which, for example, defines unique variable names for all values and one which reuses variable names.

After the students compared the solutions, they were asked to generate a list of the required steps in an engineering calculation and a list of rules for documenting engineering calculations. The instructor guided this process with verbal prompts but largely allowed the students to formulate the rules. Finally, the students were asked to list the benefits of following the prescribed format.

In both semesters, the students were then asked to complete a homework problem consisting of a relatively simple calculation of the area of a trapezoid. The problem was graded using the same detailed rubric each semester. The rubric was designed to assess whether students clearly documented their calculation process in the required format, rather than the correctness of the calculation itself. The performance of each student on the engineering calculations homework assignment was graded on a 0 to 4 scale corresponding to letter grade breakdowns, where exceptional work was given a 4 and unsatisfactory work was given a 0. A repeated-measures analysis of variance (ANOVA) [16] was completed in R [17] to assess whether the performance scores differed between the F'21 and F'22 semesters, which used the traditional and generative learning methods, respectively. In addition to the effect of semester, a nested factor of Grader (A-F) was included in the model to account for the random error between the six different graders. A *p*-value below 0.05 was considered significant in the ANOVA, and post-hoc pairwise comparisons were made with Tukey-Kramer adjusted *p*-values.

Results

Table 1 shows the number of students enrolled in the two semesters studied, as well as the number and percentage of students who submitted the homework assignment in each semester. The fact that a significant portion of students – approximately one quarter in each semester – did not submit the assignment is a trend that has been observed for a number of years in this course. The reasons for this are unknown. Although the lecture portion of the course is large and was remote for Fall 2021, both semesters included smaller recitation sections with 25-30 students each which were conducted in person. In Fall 2021, homework was collected as hard copies in person, while in Fall 2022, it was collected electronically via a learning management system. In both semesters, homework assignments and due dates were posted in writing on the learning management system, in addition to being announced in lecture.

Table 1: Enrollment counts and number of assignment submissions for semesters studied.

Semester	Total Students	Total Submissions
Fall 2021	153	111 (73%)
Fall 2022	107	82 (77%)

The scores of the engineering calculations assignment between the traditional and generative learning methods were evaluated with a repeated-measures ANOVA. Although there was a slight difference between the means of the traditional (1.9 ± 0.2, standard error [s.e.]) and generative

(2.6 ± 0.2, s.e.), there was no significant effect of learning method on the performance scores (p = 0.11). There was a significant effect of grader ($p < 0.0005$). As seen in Figure 1, two of the graders in the F'21 semester (B and C) graded the calculations assignment significantly lower than grader D in the F'22 semester. Within the F'21 semester, a significant difference was observed between graders A and B, and within the F'22 semester, a difference was observed between graders D and E. From these observations, it is unclear if the slight differences in the reported scores between the two semesters are due to the learning method.

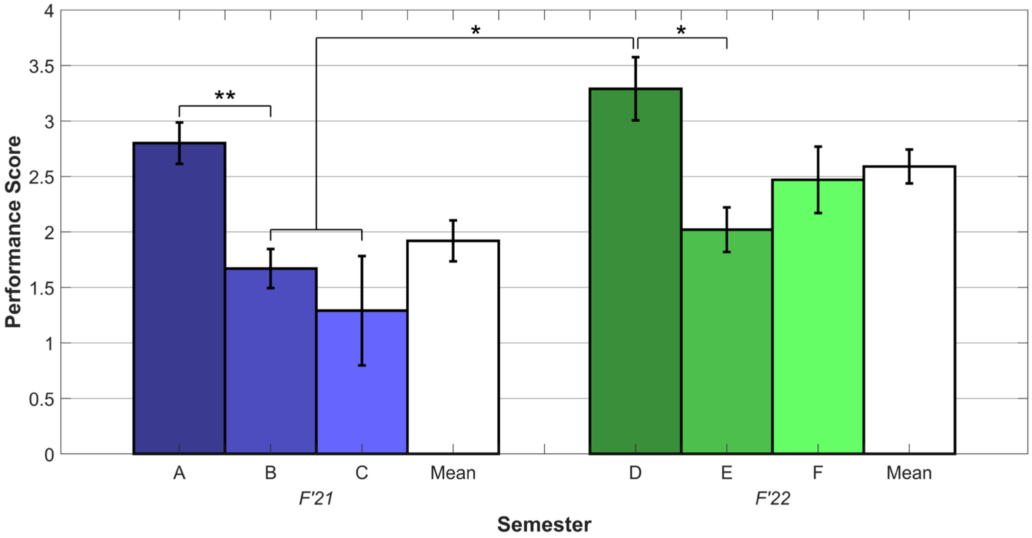


Figure 1: Performance scores of students in the F'21 and F'22 semesters broken down by Graders (A through F). While there were no significant differences between the means of the two semesters, there was a significant difference between scores of the six different graders. '*' denotes p < 0.01 and '**' denotes p < 0.0005. Error bars are reported as standard errors of the means.

There are several possible explanations for the differences among graders. All graders utilized the same rubric for grading, but partial credit could be awarded for each grading criteria, and graders may have differed in the amount of credit they would deduct for a specific type of error. Additionally, although the problem was designed with the intent of assessing problem documentation rather than computational skills, instructors in both semesters observed that a number of students mistook the legs of the trapezoid for its height, and the graders may have varied in the point deductions for this error, since it is unusual to grade an engineering assignment based primarily on clarity of presentation rather than correctness of the calculations. Anecdotally, the lecture instructor observed that students were significantly more engaged with the material during the generative learning approach, although it is difficult to isolate that effect from the course delivery format change between the two semesters, as F'21 was remote and F'22 was in-person.

In the future, it is likely that the instructors will continue with the generative learning approach due to the apparent increase in student engagement and the instructors' preference for this delivery style. However, it is clear that simply providing a detail rubric is insufficient to standardize grading between instructors in this case. In future semesters, graders will be provided with examples of student work of varying levels of performance and coached on desired grading standards in order to improve consistency of assessment.

Conclusions

Students were instructed on proper engineering calculation format in two subsequent semesters, one which used a traditional lecture format with slides and examples presented by the instructor, and one which used a generative approach of asking students to examine engineering calculations of varying quality, explain the differences, and produce a list of guidelines for good calculations. Although a small improvement in mean student performance was seen with the generative approach, it was not statistically significant, and it may have been due to the differences among individual graders. The lecture instructor did observe an improvement in student engagement in the topic when the generative approach was used, which can be a challenge in a large introductory course, so it is likely that this method will be used going forward. More study is required to ascertain whether the generative approach improves student performance in this area, and coaching of graders will be introduced in future semesters to improve consistency of assessment.

References

[1] A. Jones, "Evaluation of Canvas-Based Online Homework for Engineering," in *2017 ASEE Annual Conference & Exposition*, Columbus, Ohio, 2017.

[2] K. Evans, P. Hummel and M. Gates, "An Expanded Study to Assess the Effect of Online Homework on Student Learning in a First Circuits Course," in *2016 ASEE Annual Conference & Exposition*, New Orleans, Louisiana, 2016.

[3] M. K. Swanbom, D. W. Moller and K. Evans, "Open-source, Online Homework for Statics and Mechanics of Materials Using WeBWorK: Assessing Effects on Student Learning," in *2016 ASEE Annual Conference & Exposition*, New Orleans, Louisiana, 2016.

[4] K. Keith, "EFCOG Best Practice #65, Engineering Calculations," Energy Facility Contractors Group, 2008.

[5] Department of Energy, "TFD-ENG-DESIGN-C-10, Engineering Calculations," Hanford Site, Benton County, Washington, 2020.

[6] University of Missouri, "Calculations and Spreadsheets - Mizzou Engineering," 2023. [Online]. Available: https://engineering.missouri.edu/tech-toolbox/calculations-and-spreadsheets/. [Accessed 10 February 2023].

[7] Auburn University, "Homework Format Department of Chemical Engineering," 2002. [Online]. Available: https://www.eng.auburn.edu/~tplacek/courses/CHEN%20homework%20format.html. [Accessed 10 February 2023].

[8] R. Taraban, C. Craig and E. E. Anderson, "Using Paper-and-Pencil Solutions to Assess Problem Solving Skill," *Journal of Engineering Education,* vol. 100, no. 3, pp. 498-519, 2011.

[9] R. Osborne and M. Wittrock, "Learning Science: A Generative Process," *Science Education,* vol. 67, no. 4, pp. 489-508, 1983.

[10] R. Osborne and M. Wittrock, "The Generative Learning Model and its Implications for Science Education," *Studies in Science Education,* vol. 12, no. 1, pp. 59-87, 1985.

[11] L. Fiorella and R. E. Mayer, "Eight Ways to Promote Generative Learning," *Educational Psychology Review,* vol. 28, pp. 717-741, 2016.

[12] L. Fiorella and R. Mayer, Learning as a Generative Activity: Eight Learning Strategies that Promote Understanding, Cambridge: Cambridge University Press, 2015.

[13] G. Brod, "Generative Learning: Which Strategies for What Age?," *Educational Psychology Review,* vol. 33, pp. 1295-1318, 2021.

[14] C. Vieira, A. Roy, A. J. Magana, M. L. Falk and J. M. J. Reese, "In-code Comments as a Self-explanation Strategy for Computational Science," in *2016 ASEE Annual Conference & Exposition*, New Orleans, Louisiana, 2016.

[15] S. P. Wu, B. Van Veen and M. A. Rau, "How drawing prompts can increase cognitive engagement in an active learning engineering course," *Journal of Engineering Education,* vol. 109, p. 723–742, 2020.

[16] M. H. Kutner, C. J. Nachtsheim, J. Neter and W. Li, Applied Linear Statistical Models, Boston: McGraw-Hill Irwin, 2005, pp. 641-1208.

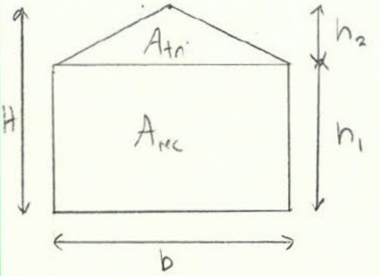
[17] R Core Team, *R: A Language and Environment for Statistical Computing,* Vienna, Austria: R Foundation for Statistical Computing, 2022.

Appendix A: Instructor-Generated Examples

The examples on the subsequent pages were provided to students in Fall 2022 as part of the generative learning activity. The first assignment is the A example, the second is the C example, and the third is the F example.

[redacted] Practice [redacted] 3/29/22 1/1

Find the total area.



Given:

$H = 3.4\,m$

$b = 3.8\,m$

$h_1 = 2.30\,m$

$A_{tri} = \frac{1}{2} b h_2$

$h_2 = H - h_1$

$h_2 = 3.4m - 2.30m$

$h_2 = 1.10\,m$

$A_{rec} = b h_1$

$A_{rec} = (3.8m)(2.30m)$

$A_{rec} = 8.74\,m^2$

Plug in:

$A_{tri} = \frac{1}{2}(3.8\,m)(1.10\,m)$

$A_{tri} = 2.09\,m^2$

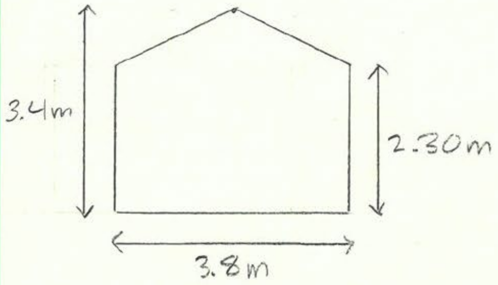
$A = A_{tri} + A_{rec}$

$A = 2.09\,m^2 + 8.74\,m^2$

$A = 10.83\,m^2$

$\boxed{A = 11\,m^2}$

[redacted] Practice [redacted] 3/29/22 1/1



Triangle:

$A = \frac{1}{2}bh$

$3.4m - 2.3m = 1.1\,m$

$A = \frac{1}{2}(3.8m)(1.1m)$

$A = 2.09m^2$

Rectangle:

$A = bh$

$A = (3.8m)(2.30m)$

$A = 8.74m^2$

$A = 2.09m^2 + 8.74m^2 = \boxed{10.83m^2}$

[redacted] Practice [redacted] 3/29/22 1/1

$2.30 \cdot 3.8 = 8.74$

$3.4 - 2.30 = 1.1$

$\frac{1}{2}(3.8)(1.1) = 2.09$

$8.74 + 2.09 = \boxed{10.83}$

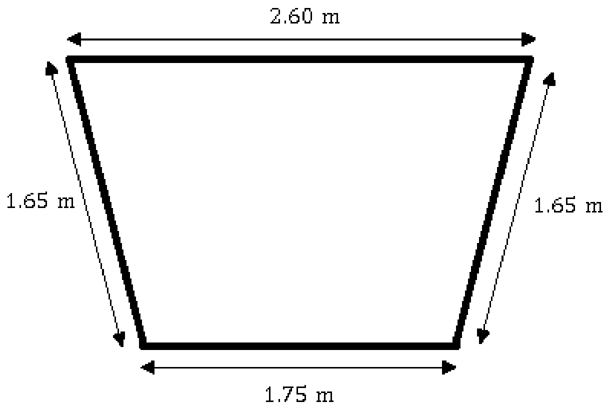
Appendix B: Calculations Assignment and Rubric

ENGINEERING CALCULATIONS ASSIGNMENT

Due at 11:59 PM on Tuesday, November 8, 2022 via Gradescope

- The assignment must be done on engineering paper, following the School of Engineering format (see Blackboard for document).
- You may only use equations found on this assignment document and the Working Knowledge document (see Blackboard for document).
- This assignment will be graded according to the rubric found on page 2.

1. Find the area of the trapezoid shown below.



RUBRIC

	Criterion	Max. Points
OVERALL	The problems are done on engineering paper	1
	Each page has a header which includes student’s name, course, recitation section, assignment title, and page numbering	3
	All writing is reasonably legible	1
	SUBTOTAL	5
PROBLEM 1	The problem is restated at the top of the page.	2
	A clear, well-labeled sketch is included.	2
	All variables are clearly and uniquely defined.	3
	All equations are written symbolically first.	3
	The solution is clear, correct, and easy to follow.	4
	Intermediate calculations are rounded to at least N+1 sig figs (full credit if not applicable).	2
	All unit conversions are done clearly and correctly.	2
	The answer is correct (value, sig figs, engineering notation, units).	2
	SUBTOTAL	20
ASSIGNMENT TOTAL		25