Project-based engineering competition in upper-level engineering laboratory

Ryan C. Cooper

Abstract

In this paper, I discuss novel features in an upper-level engineering course that have been used to enhance technical writing and problem-solving skills. I redesigned the course in Fall 2018 to prepare students to make engineering decisions and accomplish design goals. My short-term objectives were to prepare the students to start their capstone projects senior year and improve technical writing. The laboratory course includes a number of novel features: specifications grading, interactive Jupyter lab handouts, and problem- and project-based learning. Problem-solving skills were evaluated with six problem-based learning (PBL) laboratories and a Project-based learning (PjBL) contest that had a cash prize. The technical writing skills were improved using specifications grading in all seven laboratories. Students were given a detailed rubric with a pass-fail threshold. Reports that did not meet the specification for pass, were revised and resubmitted. The specifications grading provided a method for students to learn from failure. Over 50% of students increased technical writing quality. The Jupyter notebooks helped to close the gap between rational and empirical design. In project-based learning, the students designed their own set of experiments including finite element analysis and experimental procedures. The students were graded upon their approach to the problem and quantification of uncertainties in measured and predicted values. Using the 2019-2020 senior capstone students, I found a statistically significant increase in preparation for engineering design from taking the lab course with PjBL. I discuss the impacts of specifications grading, project-based learning competition, and detail the measured improvements in technical writing throughout the semesters in Fall 2018 and Fall 2019. The impacts were measured based upon a standardized rubric and qualitative assessments.

Introduction

Engineers are expected to create models, take measurements, make predictions, validate models and communicate difficult concepts. The most important ABET outcomes ranked by practicing engineers, employers, and recent graduates are 1-problem solving and 2-communication[1,2]. Problem-solving comes in two main forms, rational design including: mathematical models, computer models, and propagation of error and empirical design including: measurements, curve-fitting, and statistical models. An upper-level engineering course is the ideal place to combine these rational and empirical design approaches. As academics, we often favor rational design e.g. Newton's laws, differential equations, and thermodynamics. Students are often drawn to engineering for its empirical appeal e.g. learn by doing, hands-on creation, and create and measure approach. Rationalists and empiricists have fought for centuries, marked especially by the conflict between David Hume[3] and Immanuel Kant[4]. The divide between rational and empirical thought creates skepticism in both design methods. I see the divide between rationalism and empiricism as the same division between engineering professor and engineering student. Despite skepticism between rational and empirical approaches, engineers are expected to build innovative designs with both rational models *and* empirical measurements. We relate quantitative, rational models to quantitative, empirical measurements through statistical quantities e.g. confidence intervals and safety factors. Engineers have to communicate rational and empirical ideas to accomplish goals.

Technical writing is crucial to communicating model predictions and measured results. Despite the necessity for strong writing skills, students struggle to meet professors'[5] and employers'[6] expectations for quality writing. I use specification grading[7] to allow students to learn from failures and respond to feedback. Specification grading introduces pass-fail grading of the lab reports similar to competency-based education or mastery learning[8,9]. Students are given a detailed rubric and a minimum standard for passing the course. Failed assignments can be revised by using a token system[7]. Specification grading is meant to decrease the time and effort spent on individual assignments; this time is spent providing critical feedback[7,10]. Technical writing is a skill that every practicing engineer uses to communicate ideas and findings.

The role of an upper-level engineering laboratory is to teach the connection between rational and empirical design and technical writing. Technical writing cannot be taught in isolation from technical context[11]. It is important for an upper-level engineering class to emulate engineering design as much as possible. The combination of rational and empirical design and technical writing fits into the general approach of problem-based and project-based learning, (PBL and PjBL, respectively). The difference between PBL and PjBL is that in PBL the instructor specifies tasks to be performed in basic steps. In contrast, PjBL specifies a greater task and the students create strategies and approaches[12]. Both PBL and PjBL have shown to be effective in higher education[13,14]. Students search, solve, create, and share approaches[15] using math models and measurements, then sharing is done with technical documents or graphs. PjBL can have a positive effect on students' attitudes towards the course[16]. Competitions in PjBL helps motivate students to approach more difficult concepts in the classroom[12,17].

The goals of this upper-level engineering project-based laboratory are to improve problem-solving skills and technical writing skills. The problem-solving skills are evaluated with six PBL laboratories and a PjBL contest that with a cash prize. Rational and empirical design principals are presented in Jupyter notebooks that combine background information, data processing, and modeling. The technical writing skills were improved using specifications grading in all seven laboratories.

Methods

The course focuses on problem-solving and technical writing. The laboratory schedule is shown in Fig. 1. At the University of Connecticut department of Mechanical Engineering department, we had 215 students in Fall 2018 and Fall 2019 enroll in this course, ME3263-Introduction to Sensors and Data. In the course, Labs #0-4 and 6 are PBL activities where students are given basic steps and asked to write technical documents. Lab #5 is a PjBL activity; I specify that the class needed to measure the mass of an object using a vibrating beam. Lab #0 is used to introduce

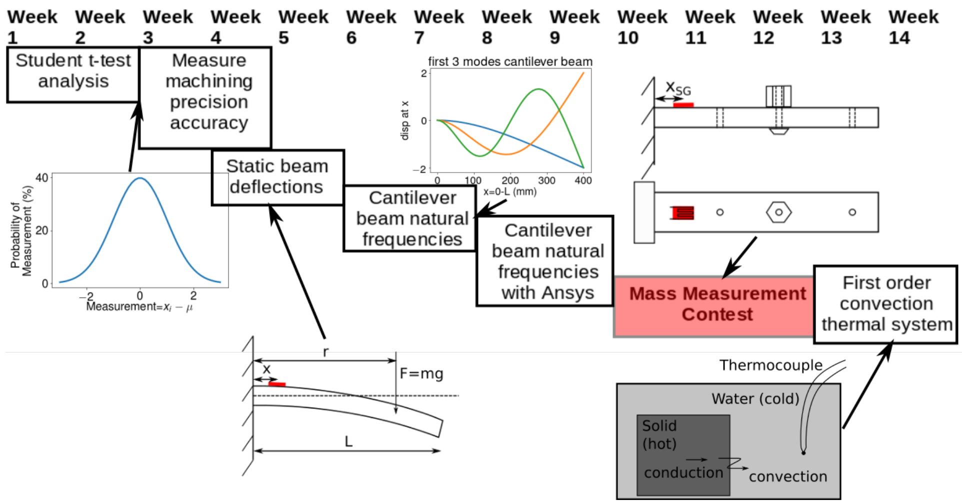


Figure 1: Laboratory schedule for the 14-week semester in upper-level engineering course. Each box represents an assignment that includes measurements, statistical analysis, and lab report. The "Mass Measurement Contest" asks students to use a combination of methods from weeks 1-9 to predict the mass of an object attached to a vibrating beam. The final two weeks are used to measure a first-order convective heat transfer problem, incorporating statistical uncertainty, finite element analysis, and verification.

statistical significance in measurements. We relate discussions of rational models and empirical measurements with statistical analysis. All students work with the same data set and submit reports graded with the rubric in Appendix A. Lab #1 asks students to quantify differences in machining methods between band saw and computer numerical control (CNC) parts. Labs #2-4 ask students to quantify differences between rational predictions using rational models and empirical measurements for static and dynamic cantilever beams. In the PjBL activity, the Lab #5 competition, the students are given the task to create a design of experiments, create a predictive model, and use engineering judgment to measure the mass of an object on a vibrating beam. The final Lab #6 included a combination of rational predictions and empirical measurements using lumped-mass assumptions, finite element analysis, and thermocouples.

The laboratory course includes a number of novel features: specifications grading, interactive lab handouts, and a PjBL competition with $150-prize. I use specifications grading for lab reports[7]. Each lab report is graded based upon a pass-fail criteria and a standardized grading rubric. Lab groups of two students are given the opportunity to revise failed lab reports with tokens. Initially, each lab group has two tokens with the opportunity to earn more during in-class discussions or extra credit assignments. Specification grading is geared towards meeting a minimum set of standards, but allowing the teaching assistants and myself to offer technical writing criticism. The goal is to help the class improve technical writing skills or at least maintain a reasonable quality for professional engineers.

The lab handouts are hosted on GitHub[18] as interactive Jupyter[19] notebooks. Students access a server to process example test data, enter their experimental data, and plot results of rational predictions and empirical analysis. The background information is rendered as html with links to resources such as Student's 1908 "The Probable Error of a Mean"[20], animations, or Wikipedia articles. The goal is to combine rational and empirical design. Thus, providing resources for capstone engineering projects and ultimately for professional engineering projects.

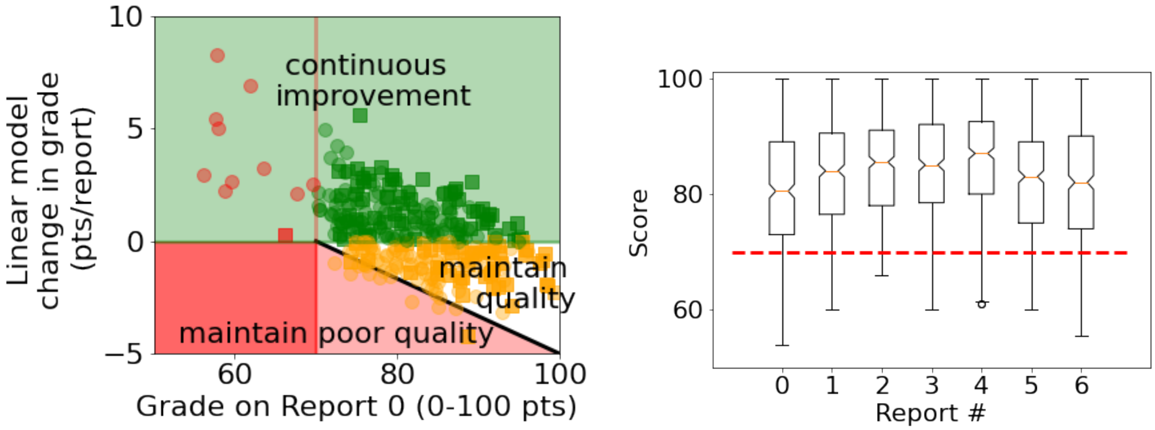
The project-based competition asks lab groups to measure the mass of an object attached to a vibrating beam. In weeks 10 and 11, the students create a design of experiments, take measurements, and create finite element analysis models. The competition does not have calibration weights, so the students have to rely on rational predictions and engineering judgments. The competition ends with the submission of their best estimate of object mass with a propagation of error and the lab report's Methods section. The lab group with the most accurate measurement is awarded a $150-prize. After the prize is awarded, the actual object masses are announced. The lab groups use week 12 to revise their approach and submit the lab report. The goal is to encourage students to create, design, and evaluate. Then, the teaching assistants and myself give clear feedback on the final error in the predicted results.

Results and Discussion

The course focuses on problem-solving and technical writing. In Fig. 2(a), the scores of each lab group is fit to a linear model to measure average increase in grade per report between Labs #0-4. The goal was to have the entire class in the green "continuous improvement"-area. In Fall 2018, 56% of the class continually improved and in Fall 2019, 59% of the class continually improved their scores. The "maintain quality" area represents students that write reports of high quality initially, but do not improve during the course of the class. In Fall 2018 and Fall 2019, the students that maintained quality accounted for 43% and 36%, respectively. The remaining 1% and 4% of the class did not improve or meet specifications for lab reports, in Fall 2018 and 2019, respectively. The F-value in a one-way repeated Analysis of Variance of lab report scores, using the Python package statsmodels[21], was 23.74 between labs 0-4 with 445 students indicating that there was a statistically significant affect on lab report grades. The grades from Labs #5-6 are shown in Fig. 2(b). Lab #5 was the PjBL contest and marked a significant increase in expectations. The results of this study, suggest that students are able to incorporate feedback from teaching assistants and myself and show improvements in technical writing. The Labs increased in difficulty, so even the groups of students that maintained their grade at the specified level show marked improvement in communicating difficult concepts.

I found specifications grading in technical writing to be an effective method of evaluation. The grades are normally distributed with the class mean increasing from 80 to 85 points. One argument against specifications grading is that students may not be motivated to increase their grade because once the grade is above passing there is no incentive to improve. I find a clear increase in grades throughout the semester, and the students that were in the "maintain poor quality" regime did fail and redo lab reports. The students that did not improve found great difficulty in Labs #5-6, most failing those assignments and revising their work. The specifications grading also has the most noticeable effect on under-performing students. The students that failed Lab #0 had an average grade increase of 5 pts/report. This increase would result in a score of 85-90 on these students Lab #6 reports, if the progress was sustained and labs did not become more demanding.

The PjBL Lab #5 activity results are plotted in Fig. 4. The histogram of errors based upon reported results demonstrate the range of effectiveness of each lab group's experimental work. In



(a)

(b)

Figure 2: Plotted above in (a) is the average change in lab report grade as a function of the first Report #0. The specification for passing Report #0 is shown as a red line at 70 points. The green area above the "Linear model change in grade"=0 shows the students that continuously improved their report grades throughout the semester. The dark red section in the lower-left, that has no student data, would be students that performed poorly and continued to decrease quality. The light-red section between 70 and 100 are the students that decreased quality to the point of risking failing Report #6. The yellow section between 70 and 100 above the orange risk section are students that decreased quality, but maintained high enough marks to not risk failing lab reports. There are three populations of students from Fall 2018 □ markers and Fall 2019 ○ markers: Red indicates students that failed Report #0, but their scores increased throughout the semester, Green indicates students that passed Report #0 whose scores continued to increase throughout the semester, and orange are students that passed Report #0, but their scores decreased throughout the semester. The orange marks in the red sections, "maintain poor quality" were at risk of failing other lab reports. In (b), box plots of the scores from 2018 and 2019 on reports 0-6 are plotted. The median is shown by a horizontal line, the notches indicate the confidence interval, the whiskers denote the range of scores, with outliers marked as circles, and the upper- and lower-quartiles are shown by the boxes above and below the median lines. The red-dashed line indicates the specification for a passing grade on the reports.

Fall 2018 and Fall 2019, the average and standard deviation in error to measure a 32-g object was 18.3 ± 32.8 g and 11.4 ± 26.7 g, respectively. While top three most accurate reports had errors less than 4%. The competition provides specific feedback to lab groups, and a non-grade-based metric to evaluate student effort and learning.

This PjBL Lab qualitatively had the highest enthusiasm and participation from the students. Student SET responses included, "I liked the mass measuring contest!", "I liked using ANSYS and the competition.", "I liked the competition where the answer was unknown. I think that was the most beneficial thing we did and I think more of those labs would be helpful." Attendance to announce winners of the contest was not mandatory, but over 90% of the class was present. Students compared answers, studied methods, and results. After the object masses were given to the class, they revised their methods one more time to reduce errors in their data collection and processing. These competitions work best when the learning happens whether or not the group wins[12]. The benefit of the contest was the increased enthusiasm in studying beam dynamics and finite element methods. Even students that had very high errors demonstrated finite element models convergence and fast fourier transform analysis of natural frequencies of cantilever beams.

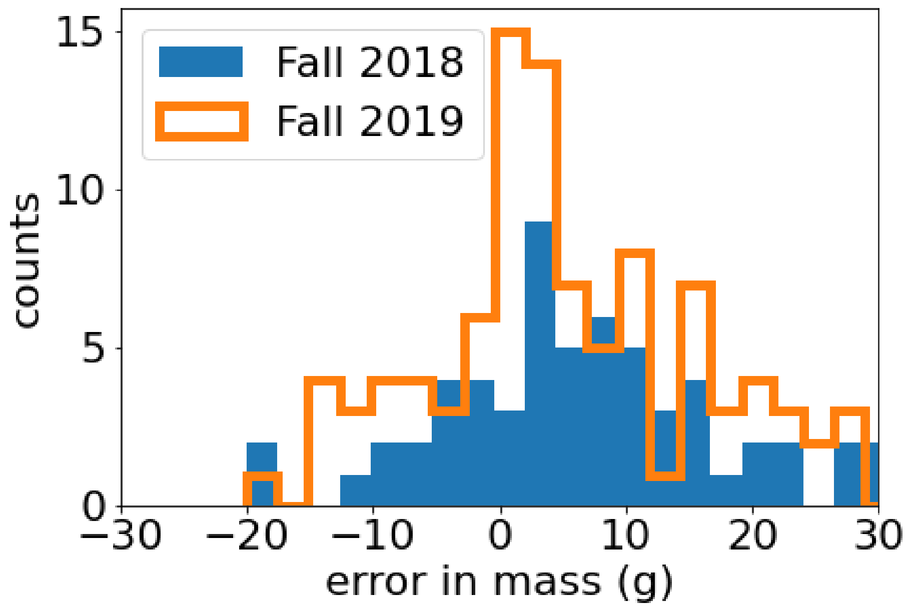


Figure 3: Plotted above is a histogram of the reported errors from Fall 2018 and Fall 2019 for the mass measurement contest. The average error in mass reported in Fall 2018 and Fall 2019 was 18 ± 33 g and 11.4 ± 27 g, respectively with error reported as standard deviation. The actual mass measurements were 32 ± 2 g. The histogram is the error=(reported value - the actual value).

I polled the 2019-2020 senior capstone project teams that took this project-based upper-level engineering lab course in either Fall 2018, 2019, or not at all. Students' comments about the course included "Was a great and helpful class", "Great class! Very helpful for senior design", and "ME3263 was a great course for technical writing." The students were asked how useful each skill that was introduced in this course is in relation to accomplishing a senior capstone project. Over 50% of the class of 270, agreed that all eight skills were useful and 50% of the class considered technical writing to be a *crucial skill*. The last question in the survey is: "How prepared did you feel starting senior design with your background from this course?" Of the students that took the course in Fall 2018 and Fall 2019, over 45% felt prepared and students that hadn't taken the course less than 30% felt prepared. Using a one-way analysis of variance on the responses (0:unprepared-4:very prepared), 145 students from Fall 2018 and 2019, and 17 N/A, the f-statistic=4.43 with a p-value of 0.04. While, considering just the difference between Fall 2018-Fall 2019, the f-statistic is 0.01 and p-value of 0.93. There is a statistically significant difference between students that took the PjBL course and those that did not. This measurement gages the students' perceived preparation for the senior capstone project.

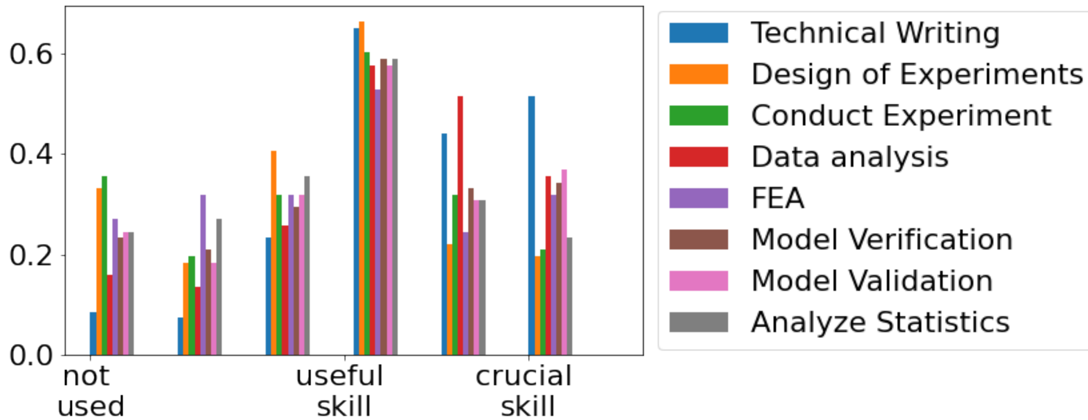


Figure 4: Plotted above is a histogram of the responses from senior capstone project students that either: took the project-based laboratory course concurrently with capstone, in the previous year, or not at all. The students were asked to rate the necessity of eight problem-solving and technical writing skills that were introduced in this project-based laboratory course.

Conclusions and Future Work

In conclusion, this course included a number of novel features: Problem- and Project-based learning (PBL and PjBL), interactive lab handouts via JupyterHub, and specifications grading. PBL and PjBL increased student motivation and confidence when beginning senior capstone projects. The PjBL competition was a welcomed success by students. Most lab groups excelled in rational and empirical design processes for the competition. Groups that did not meet expectations revised their work and continued to improve technical writing quality. The specifications grading provided a method for students to learn from failure and over 50% of students increased technical writing quality. Access to interactive notebooks increased the variety and use of the lab handouts. Using Jupyter notebook handouts created a medium that mixed background information, data processing, and simple engineering models. The Jupyter notebooks helped to close the gap between rational and empirical, hands-on design. The project-based upper-level engineering lab course redesign has been a success. Using the 2019-2020 senior capstone students, I found a statistically significant increase in preparation for engineering design from taking the lab course with PjBL.

Some ongoing work will be to evaluate the effectiveness of individual changes in the course. Specifications grading is a novel way to asses engineering students' technical writing skills. I believe the process of revising reports provides much-needed practice for students, but it would be interesting to see what fraction of the class has measurable increase in writing quality without this process. I assume the PjBL competition is a big motivational and preparational tool, but there may be other sources of motivation and preparation. Some future work is to compare results between a competition-based PjBL and PjBL component with no competition and to incorporate senior capstone grades into the analysis of the effectiveness of the course.

References

[1] H. J. Passow and C. H. Passow, "What Competencies Should Undergraduate Engineering Programs Emphasize? A Systematic Review," *Journal of Engineering Education*, vol. 106, no. 3, pp. 475–526, jul 2017.

[2] D. L. Evans, G. C. Beakley, P. E. Crouch, and G. T. Yamaguchi, "Attributes of Engineering Graduates and Their Impact on Curriculum Design," *Journal of Engineering Education*, vol. 82, no. 4, pp. 203–211, oct 1993.

[3] D. Hume, *A treatise of human nature*. Dover, 1739.

[4] I. Kant, *Critique of pure reason*. MacMillan, New York, NY, 1781.

[5] T. Lillis and J. Turner, "Student Writing in Higher Education: Contemporary confusion, traditional concerns," *Teaching in Higher Education*, vol. 6, no. 1, pp. 57–68, jan 2001.

[6] S. Conrad, "A Comparison of Practitioner and Student Writing in Civil Engineering," *Journal of Engineering Education*, vol. 106, no. 2, pp. 191–217, apr 2017.

[7] L. Nilson and C. Stanny, *Specifications Grading: Restoring Rigor, Motivating Students, and Saving Faculty Time*. Stylus Publishing, 2015.

[8] B. S. Bloom *et al.*, "Handbook on formative and summative evaluation of student learning." 1971.

[9] C.-L. C. Kulik, J. A. Kulik, and R. L. Bangert-Drowns, "Effectiveness of mastery learning programs: A meta-analysis," *Review of educational research*, vol. 60, no. 2, pp. 265–299, 1990.

[10] B. Blackstone and E. Oldmixon, "Specifications Grading in Political Science," *Journal of Political Science Education*, vol. 15, no. 2, pp. 191–205, apr 2019.

[11] H. J. Passow, "Which ABET Competencies Do Engineering Graduates Find Most Important in their Work?" *Journal of Engineering Education*, vol. 101, no. 1, pp. 95–118, jan 2012.

[12] J. C. Burguillo, "Using game theory and competition-based learning to stimulate student motivation and performance," *Computers & education*, vol. 55, no. 2, pp. 566–575, 2010.

[13] S. Carlile, S. Barnet, A. Sefton, and J. Uther, "Medical problem based learning supported by intranet technology: A natural student centred approach," in *International Journal of Medical Informatics*, vol. 50, no. 1-3. Elsevier Sci Ireland Ltd, jun 1998, pp. 225–233.

[14] J. Morrison, "Where now for problem based learning?" *Lancet*, vol. 363, no. 9403, p. 174, jan 2004.

[15] H. Awang and I. Ramly, "Creative thinking skill approach through problem-based learning: Pedagogy and practice in the engineering classroom," *International journal of human and social sciences*, vol. 3, no. 1, pp. 18–23, 2008.

[16] S. Bell, "Project-based learning for the 21st century: Skills for the future," *The clearing house*, vol. 83, no. 2, pp. 39–43, 2010.

[17] S. Michieletto and E. Pagello, "Competitions and industrial tasks as a way to learn basic concepts in robotics," in *2018 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*. IEEE, 2018, pp. 173–178.

[18] R. Cooper, "Introduction to sensors and data," https://github.com/cooperrc/sensors_and_data, 2021.

[19] T. Kluyver, B. Ragan-Kelley, F. Pérez, B. E. Granger, M. Bussonnier, J. Frederic, K. Kelley, J. B. Hamrick, J. Grout, S. Corlay *et al.*, "Jupyter notebooks-a publishing format for reproducible computational workflows." in *ELPUB*, 2016, pp. 87–90.

[20] Student, "The probable error of a mean," *Biometrika*, pp. 1–25, 1908.

[21] S. Seabold and J. Perktold, "statsmodels: Econometric and statistical modeling with python," in *9th Python in Science Conference*, 2010.

Appendix A

Section	Category	Unacceptable (0)	Acceptable (½)	Good (¾)	Excellent (1)	Weight	Score
Introduction	first sentence is interesting and grab's reader's attention					2	
	Problem or hypothesis is stated clearly					6	
	Physical principles are stated clearly					6	
	other applications are discussed					4	
	reason for experiment is stated clearly					4	
Methods	Relevant experimental details are discussed					4	
Materials	equipment and environmnet discussed"					4	
	Results and Discussion are not mentioned					4	
Results and Discussion	Output of experiments are presented					8	
	principles from Introduction are applied to data					8	
	analysis/model/theory is presented					8	
Conclusion	Summarizes report					2	
	relationship between results and analysis (or model or theory) is discussed					4	
	Most important results are summarized					4	
	consequences of results are discussed					4	
	reservations or limitations of study are discussed					4	
References	significant previous work/textbooks are cited					4	
	references are complete					4	
Figures	Figures are easy to interpret					8	
Overall	Spelling/grammar					2	
	significant digits are correct					2	
	flow					2	
Appendix	contains essential material that would interupt flow					2	
						100	