AC 2009-2209: A METHOD OF ASSESSING EXPERIMENTAL DESIGN IN MECHANICAL ENGINEERING LABORATORIES

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A Method of Assessment to Examine Experimental Design in Mechanical Engineering Laboratories

Students in the mechanical specialization at Mercer University are currently required to take two general mechanical engineering laboratory courses—one in the third year of the curriculum and the other in the fourth year. The first of these courses begins with seven or eight single period laboratories in which the students are directed to complete a well-defined set of procedures and perform simple analyses. In an effort to more formally introduce experimental design into the laboratory experience, this course ends with a three project sequence in which students are provided with an experimental objective (e.g., determine the coefficient of performance of a vapor-compression refrigeration system as a function of condenser pressure) and information regarding the function of an experimental apparatus. In two 3-hour lab periods, students are expected to independently develop and verify a procedure for accomplishing the objective, execute their procedure, and report the results. The purpose of the second course, the senior-level capstone laboratory experience, has always been to have students successfully design an experimental solution to more complex engineering problems, building upon the knowledge gained during the junior-level experience. The senior lab consists of only two experimental objectives, and students have seven weeks to define, execute, and conduct the series of experiments required to meet the objective. This laboratory structure has now been in place for about ten years and has been formally assessed for one and a half ABET cycles, including two ABET site visits. This paper has three main goals: (1) to present an overview of the current structure of these labs at Mercer University, (2) to examine details and results of the School of Engineering's assessment scheme for demonstrating "an ability to design and conduct experiments, as well as to analyze and interpret data" when applied at the specialization level, and (3) to both quantitatively and qualitatively compare performance in the two lab courses to determine whether the junior-level experience is sufficient preparation for the senior-level experience.

Introduction

Laboratory experiences are an important component of mechanical engineering (ME) education. In lab courses, students learn to identify experimental objectives, apply basic measurement techniques, collect and evaluate data, and write technical reports. In addition, senior-level students often must design a set of experiments for achieving an open-ended research objective. The Accreditation Board for Engineering and Technology (ABET) requires that engineering programs demonstrate that their students attain eleven outcomes, including one that most specifically addresses laboratory courses[1]:

"Engineering programs must demonstrate that their students attain the following outcomes: . . . [including] an ability to design and conduct experiments, as well as to analyze and interpret data . . ."

At the Mercer University School of Engineering (MUSE), the mechanical engineering laboratory sequence consists of two courses. MAE 302L is a two-credit course that most students schedule during the spring semester of their junior year. One of the desired (if not explicitly stated) results of MAE 302L is to fully prepare students for MAE 402L, which is the senior-level laboratory experience that most students schedule during the fall semester of their senior year. The major difference between the two courses is the open-ended nature of MAE 402L. Specific differences will be discussed later.

There are two hypotheses under test in this paper. The first deals with ABET and/or SACS (Southern Association of Colleges and Schools) accreditation, and can be stated as:

Successful completion of MAE 302L and MAE 402L by MUSE students demonstrates adequate proficiency in the areas of designing and conducting experiments, and analyzing and interpreting data.

The tests used to investigate this hypothesis are both objective (e.g., the course assessment scheme developed by MUSE) and subjective (e.g., faculty observations and impressions). The second hypothesis deals with the notions of "threading" concepts and skills throughout the curriculum, as well as quantifying the degree to which related experiences build upon one another[2-3]:

Successful completion of MAE 302L adequately prepares students for the subsequent course, MAE 402L, which is more rigorous.

Likewise, the tests used to investigate the second hypothesis are also objective and subjective.

Description of MAE 302L

Junior-level students enrolled in MAE 302L spend one hour per week in a traditional lecture setting, during which time they are introduced to subject matter including uncertainty and statistical analyses, dynamic system measurement, and instrumentation. In addition, students are required to conduct simple, closed-ended laboratory experiments on the following topics: hardness testing, shear stress, beam bending, column buckling, tensile testing, and temperature measurement. The lab instructor provides the students, who work in small teams of 2-4 members, with a complete description of the current experiment. Requirements for the students include setting up the relevant equipment, performing the indicated tests, and recording their observations, all in the allotted three hour lab period. Each group must turn in a professional written report one week later.

Following the completion of the “canned” labs, students are required to conduct three, open-ended experiments over the rest of the term (6-7 weeks). Characteristic problem statements for these labs are as follows:

- **Fluid Flow** – Calculate mass flow rate using the cantilevered weight technique and using the venturi tube. Also, determine the best locations on the venturi for estimating mass flow rate.
- **Refrigeration Cycle** – Determine the coefficient of performance of the refrigeration cycle under various evaporator and condenser pressures.
- **Heat Transfer** – Determine the thermal diffusivity of an aluminum bar.

Student groups are provided little additional information and work on each experiment for two weeks. During the first week, students familiarize themselves with all relevant equipment and determine a procedure for conducting the experiment that they will execute the following week. Groups are required to submit a lab plan prior to the week two activities. Groups rotate among the three labs until all have been completed.

Description of MAE 402L

In MAE 402L, each group of 3-4 students is expected to solve two open-ended problems during the semester (groups are nominally allocated seven 3-hour class periods for each problem). Two typical problem statements are as follows:

- Determine an appropriate convective correlation for free convection heat transfer from a flat plate. An analysis for a single plate orientation/geometry is required. Compare your result with a "standard" correlation for your test geometry.

- You are a product engineer for Cedar Ridge Forge, Inc. (CRFI); a manufacturer of forged industrial products. One of your most profitable products is pole climbers, used by rural telephone service workers and tree harvesters. Until recently, CRFI had been the dominant supplier to the domestic climber market, primarily because CRFI's climbers were the lowest price climbers available. Recently, the firm has been losing market share in the climber market because the old line was plagued by fatigue cracking in the shank of the climber. You have proposed a change in material for the shank to AISI/SAE 4140 steel. Your largest customer will agree to the material change and its resulting price increase if the following conditions can be achieved:

    1. the shanks will be 100% tempered martensite in the maximum thickness of 0.25 inch;
    2. the shanks have a tensile strength of at least 225 ksi;
    3. the ductility of the shanks be at least 8%;
    4. the yield strength of the material be at least 180 ksi.

    Select a heat treatment for AISI/SAE 4140 steel and design an experimental program that will demonstrate that your heat treatment process improves the climbers[4].

Groups receive the problem statement and a list of available equipment, materials, and tools (some of which may not be relevant) at the first meeting, and must turn in a lab plan (completed individually) at least 1-2 days before the second meeting. Each group determines its experimental procedures based on the individual plans submitted by the group members.

Evaluations of Student Performance — Assessment

Student reports from this senior level capstone laboratory are the sole basis of the performance assessed for use in determining whether or not program outcomes have been achieved for the mechanical specialization. The statement of program outcomes for the Mercer University School of Engineering proposes that, among a number of other engineering and societal capabilities, graduates will be able to "design and conduct experiments and analyze data."[5] This outcome and its assessment are intended specifically to address ABET engineering program criterion 3(b)—"Engineering programs must demonstrate that their students attain the following outcomes: . . . (b) an ability to design and conduct experiments, as well as to analyze and interpret data . . ."[1] as well as SACS comprehensive standard 3.3.1—"The institution identifies expected outcomes, assesses the extent to which it achieves these outcomes, and provides evidence of improvement based on analysis of the results in each of the following areas: 3.3.1.1 educational programs, to include student learning outcomes . . ."[6]

Within the Mercer School of Engineering this assessment is conducted by an evaluation of student work from one open-ended experiment assignment. All reports for this lab assignment are assessed by a team of three faculty members [usually including the course instructor(s)]. The faculty members assess each of four tasks separately[7,8]: design of experiment, conduct of experiment, analysis of data, and interpretation of data. Each lab group's performance with respect to each task is scored on a 1 to 5 scale; where 1 represents unacceptable performance, 3 represents acceptable performance, and 5 represents excellent performance. An overall score for each group is calculated as the grand average of the three faculty member scores for the set of four tasks on the selected assignment. The outcome is judged to have been achieved if 70% or more of the students/teams have a grand average of 3.0 or higher. The standard form for this activity is shown in Appendix A. Within the mechanical specialization, the four tasks—design, conduct, analysis, and interpretation—are each subdivided into five related sub-tasks that students are expected to address in their final lab reports. This sub-division is shown in Appendix B.

The mechanics of the assessment process consist of each evaluator reading a report and determining (to the evaluator's satisfaction) which of the expected sub-tasks have been adequately completed. If, for example, any four of the expected sub-tasks in a group have been adequately reported, then a score of "4" is transferred to the team evaluation sheet for the appropriate category. These twelve individual scores thus obtained (four per evaluator) are subsequently averaged and the "grand average" is determined for each lab group.

Implementation of this assessment scheme has turned out to be reasonably straight-forward. Faculty members undertaking the evaluation are able to score each report in real time without having to refer back to other reports to maintain a comparative basis for evaluation. Post-processing of results consists only of determining the grand average for the report from the individual faculty assessments. The underlying handicap of this scheme appears to be that, after three cycles of implementation, most lab groups fail to achieve the 3.0 or higher expected grand average. While evaluator score tallies within task groups characteristically do not vary widely, the detail with which the score was determined may—e. g., one evaluator may feel that sub-tasks 1, 3, and 5 were properly managed, while a second evaluator may feel that sub-tasks 2, 4, and 5 were the sub-tasks satisfied. These discrepancies make specific closure of the feedback loop difficult—especially since neither of the lab courses includes course learning objectives specifically directed at each sub-task. What does emerge anecdotally from this assessment scheme when evaluated by the laboratory course instructors is a common sense that most of the deficiencies noted lie in the poor quality of the written report rather than in the overt omission of expected outcomes. Generally speaking, in designing an experiment, most student groups are **observed** to identify applicable theory, operate relative to a reasonable problem statement they have defined, evaluate a range of variables, appropriately define a repeatable and effective procedure, etc., but they seem to be unable to consistently write a technical laboratory report that clearly indicates that these tasks have been accomplished. Similar statements can be made with regard to conduct of the experiment and the analysis of experimental data. The one category that does not lend itself to consistent in-class/lab observation of student activity is the interpretation of data. As this is the most open-ended of the experimental tasks assessed, it might be expected that this area could generate the most legitimate concern. As applied in the mechanical specialization, the MUSE assessment scheme would do little to alleviate that concern, but, again, discerning whether or not the difficulty is fundamentally in the student interpretation or in the reporting of the student interpretation is open to debate. While in-lab discussion can elicit pertinent observations from most groups, it also seems equally clear that students do not generally grasp the relevance of these in-class (and often instructor initiated) discussions with regard to the interpretation of experimental results they are trying to report.

It is certainly plausible that these shortcomings can be addressed in the curriculum. All engineering students at MUSE take two courses related to technical communication (EGR 108, Professional Practices, and TCO 341, Technical Communication). What appears to be missing from the focused content of both of these courses is a specific effort to address issues of technical writing. Alternatively, within the mechanical specialization technical electives could be modified to allow more academic credit to be assigned to either MAE 302L or MAE 402L (or both).

Evaluation of Student Preparedness — Grades

One of the most difficult instructor tasks involved in capstone laboratories is evaluating student performance and assigning grades. The difficulty is related to the unavoidable subjectivity of the evaluation and the intrinsic muting of individual contributions whenever students work in teams. In MAE 302L, individual contribution in the laboratory is assessed through peer reviews and evaluations[9] (see Appendix C). MAE 402L has a more definitive individual component, in that 35% of the final grade is attributed to the student's individual lab plan. A grading rubric for both courses is provided in Appendix D.

Table 1 shows the aggregate change in students' grades after completion of the MAE 302L-MAE 402L lab sequence. For example, of the 109 students who completed the sequence, 44 (approximately 40%) improved their grades in the senior-level course. The data were further evaluated using a paired t-test to investigate differences between the students' mean grade change. The 95% confidence interval (CI) for the mean difference is (-0.0449, 0.2449) with a p-value = 0.1588. These results indicate that there is no statistical difference between final grades obtained in MAE 302L and MAE 402L. A caveat to this analysis is that different instructors teach the two courses, which likely introduces bias (i.e., grading inconsistencies). In addition, students may forget the nuances of experimental design introduced in MAE 302L during the summer before their senior year.

Table 1. Change in students' grades (MAE 302L - MAE 402L)

	Number	% of Total
Improved	44	40.4
No change	24	22.0
Worsened	41	37.6
	n = 109 students	

Evaluation of Student Preparedness — Faculty Observations

For the most part, students in MAE 402L are able to decipher a general statement of research objectives, design simple experiments related to the overall goal, and collect meaningful data in a systematic and timely fashion. The MAE faculty is pleased with the students' "ability to design and conduct experiments, as well as well as to analyze data." Where students tend to fall short of faculty expectations, however, is in their ability to "interpret" the data they collect. For example, the specific experiments for determining the heat transfer coefficient (h) and viscosity (μ) designed by typical student groups working on the heat transfer laboratory are of high quality. However, the tables, graphs, and accompanying text used to report their findings are inadequate. The missing component from the engineering educational experience at MUSE appears to be specific, intentional training in technical writing, although the curriculum can be easily modified to address this concern, as discussed in the previous section.

An interesting addendum to the shortcomings identified at MUSE is the self-reported writing proficiency of practicing engineers, who report writing as a professional strength, and who correlate years of education with writing aptitude[10]. This could indicate that practicing engineers undergo significant on-the-job training in technical writing.

Conclusions

Both metrics of assessment (the ABET/SACS assessment and the traditional grading evaluation) have uncovered the same basic weakness at the end of the senior level capstone laboratory in the mechanical specialization. The missing component from this aspect of the engineering educational experience at MUSE appears to be specific, intentional training in technical writing. The persistence of this observation over four full assessment cycles (eight years) indicates that curricular changes may be appropriate in order to address this need. Within the mechanical specialization this could be achieved by increasing the credit in the junior lab course in order to include more focused writing content or, school-wide, by changing the current focus of the technical communication classes.

Acknowledgements

The authors would like to acknowledge Drs. Monika Bubacz, Thomas Cook, Ohchang Jin, Phil Metz, and Loren Sumner for their past and continued contributions to the mechanical engineering laboratories at Mercer University.

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Appendix A

MUSE Assessment of BSE Outcome 4
Design and Conduct Experiments and Analyze and Interpret Data
Individual Student/Team Evaluation Sheet

Course: ________________ **Semester:** _____________

Faculty Evaluators: ____

Laboratory Experiment: ____

Student/Team Members: ____

Evaluate the attached laboratory report in terms of performance in each of four task areas, where each task area is defined in terms of the following typical activities:*

Design of experiment
Identify applicable theory, construct appropriate hypothesis or problem statement, formulate control and evaluating variables, choose measure(s) of effectiveness by which experimental outcome(s) will be evaluated, predict experimental uncertainties, combine information for experiment from multiple sources
Conduct experiment
Consider measurement errors in instrumentation, anticipate and minimize experimental disruptions, follow ethical protocols when collecting data, document collection procedures so that experiment can be repeated, anticipate and minimize data errors via pilot study.
Analysis of data
Select and explain different methods of analysis (descriptive and inferential) and depth of analysis needed, use appropriate tools to analyze data, apply statistical procedures were appropriate, organize information into meaningful categories
Interpretation of data
Recognize how results relate to or differ from theory or previous results, verify and validate experimental results, question whether constraints hold in both experiment and real world, interpret results with respect to assumptions and constraints, assess the accuracy and precision of the results.

Evaluate each student/team's performance with respect to each of the four task areas using a 1, 2, 3, 4, 5 scale; where 1 represents unacceptable performance, 3 represents acceptable performance and 5 represents excellent performance

Faculty Evaluation Summary	**Faculty Member 1**	**Faculty Member 2**	**Faculty Member 3**
Design of experiment	______	______	_______
Conduct experiment	______	______	_______
Analysis of data	______	______	_______
Interpretation of data	______	______	_______

Calculate the grand average for the student/team's performance as the average of the 12 scores listed above.

Grand Average: ______________

* Typical activities from *EC 2000 Outcome Attributes: Definition and Use*, by Besterfield-Sacre, Shuman, Wolfe, Atman, McGourty, Miller, Olds, and Rogers, University of Pittsburgh, 2000.

Appendix B

LAB GROUP/PROJECT: ____________________ EVALUATOR: _________________

DESIGN of experiment

1. identify applicable theory _____
2. construct appropriate problem statement _____
3. evaluate range of control variables _____
4. define procedure _____
5. reference information from multiple sources _____

CONDUCT experiment

1. experimental uncertainty/control measurement errors _____

2, anticipate experimental disruptions _____

3. follow safety protocols _____
4. document collection procedures _____
5. perform pilot study _____

ANALYSIS of data

1. select and explain method of data analysis _____
2. use appropriate analysis tools _____
3. apply appropriate statistical procedures _____
4. organize information into meaningful categories _____
5. experimental uncertainty used in results _____

INTERPRETATION of data

1. relationship of results to theory _____
2. validate experimental results _____
3. interpret results _____
4. assess accuracy and precision of results _____
5. recommendations for future work _____

Appendix C

Self/Peer Team Assessment

Name_______________________________ ***Date***______________________ ***Lab***____________

1. Please circle the rating that best describes your team for each of the three items below:

a. Did all members of the group share in the team's responsibilities?

Some members did no work at all	A few members did most of the work	The work was generally shared by all members	Everyone did an equal share of the work

b. Which of the following best describes the level of conflict at group meetings:

No conflict, everyone seemed to agree on what to do	There were disagreements, but they were easily resolved	Disagreements were resolved with considerable difficulty	Open warfare: still unresolved

c. How productive was the group overall?

Accomplished some but not all of the project's requirements	Met the project requirements but could have done much better	Efficiently accomplished goals that we set for ourselves	Went way beyond what we had to do exceeding even our own goals

2. Please rate yourself and each team member on how well the following phrase describes your team's work:

Disagree	Tend to disagree	Tend to agree	Agree
1	**2**	**3**	**4**

Team Member Name or Initials:

Self:			

a. Failed to do an equal share of the work				
b. Kept an open mind/was willing to consider other's ideas				
c. Was fully engaged in discussions during meetings.				
d. Took a leadership role in some aspects of the project.				
e. Helped group overcome differences to reach effective solutions.				
f. Often tried to excessively dominate group discussions.				
g. Contributed useful ideas that helped the group succeed.				
h. Encouraged group to complete the project on a timely basis.				
i. Delivered work when promised/needed.				
j. Had difficulty negotiating issues with members of the group.				
k. Communicated ideas clearly/effectively.				

Section 3: Write a brief description of the problems you encountered in working with this group and how they were resolved.

____

Section 4: Please distribute 100 points to your team. Each team member (including yourself) should get the points appropriate to his/her contribution to the team's efforts. The total points should add up to 100.

NOTE: Please make this a meaningful assessment instrument. Use integers only. Avoid giving each member the exact same score.

Name:	**# of Points**
(Self)	
Total	**100**

Adapted from a self/peer assessment instrument developed by members of the Synthesis Coalition and reported in Van Duzer, E. & McMartin, F. (1999). Building better teamwork assessments: A process for improving the validity and sensitivity of self/peer ratings. Proceedings of the American Society for Engineering Education 1999 Annual Conference.

Appendix D

MAE 302L/MAE 402L
Experiment Grade Sheet

Group Members:

Experiment:

	Possible Points	Points Received
ABSTRACT		
Summary of Work	2	
Presentation of Conclusions	3	
INTRODUCTION		
Remarks	5	
Theory	5	
METHODS		
Materials Used	5	
Experimental Procedures	10	
RESULTS		
Calculations	10	
Facts Obtained	10	
DISCUSSION		
Interpretation	15	
Summary and Conclusions	15	
REFERENCES	5	
OVERALL	15	
TOTAL	**100**	

Instructor comments: