2006-2534: NONE OF MY LAB DATA MAKES ANY SENSE - LEARNING TO INTERPRET AND REPORT EXPERIMENTAL RESULTS

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At the University of South Carolina, Jed Lyons is a Professor of Mechanical Engineering. He has developed laboratory experiments for freshman engineering, engineering materials, measurements and instrumentation, and mechanical systems. He currently serves on the advisory board for the Center for Teaching Excellence, and is Chair of the Faculty Committee on Instructional Development Director, Director of the Center for Engineering and Computing Education, and Principal Investigator of a NSF Graduate Teaching Fellows in K-12 Education award. With ASEE, he has held leadership positions in the Mechanical Engineering Division and K-12 Engineering and Pre-College Outreach Division and serves as USC's Campus Representative. Jed is interested in how we learn to be engineers.

None of My Lab Data Makes Any Sense: Learning to Interpret and Report Experimental Results

Abstract

Many laboratory courses are designed to illustrate to students that the theory taught in lecture is correct. If experimental data doesn't match a theory, students tend believe that that there is something wrong with their data. To compensate for their "bad data", sometimes students may be provided with "good data" from the instructor, or they may report that it is their fault that the data doesn't match the theory and simply cite "human error" as the cause of the discrepancy. Such experiences do little to help the student develop critical thinking skills or the ability to their own design experiments. This paper illustrates how the concept of "learning from mistakes" can be used as instructional strategy in engineering laboratory courses. Three experiments from a junior-level mechanical engineering course on Measurements and Instrumentation at the University of South Carolina are provided as examples of this instructional approach. Topically, the experiments deal with the average force that humans apply when squeezing an object between their thumb and forefinger, how an internal combustion engine's piston position is related to the crank angle, and how to conduct a thermodynamic energy balance on an air conditioner. These and other experiments in the course are set up so that students encounter problems that force them to think critically, improving their ability to design experiments. The effect of having students rewrite graded laboratory reports to improve technical writing skills is also discussed.

Introduction

The learning objectives of the Measurements and Instrumentation laboratory course taken by our mechanical engineering students are to design and conduct experiments, explain the operating principles of common instrumentation, use statistics to analyze experimental results, use experimental results to evaluate theoretical models, organize and write laboratory reports, and organize and give an oral presentation. Historically, the course included a large number of laboratory experiments that were performed every semester the course was offered. That format gave the students considerable experience conducting experiments, but addressed the other course objectives to lesser extent.

For example, teaching students how to organize and write laboratory reports was difficult because many students had ready access to lab reports that were written in previous semesters. Students were not forced to think about what they should include in their laboratory report or how to structure it so that the experimental results are conveyed clearly, because they had example reports to follow or copy. These students were not forced to think critically while comparing their results to a theory, because former students had done that for them.

To mitigate the issues associated with old lab reports being available to students, the instructor has taken the approach to develop new experiments every semester. Although the number of experiments was reduced from ten to five, the workload of creating five fully-functional and debugged experiments every semester became significant. Often, the quickly drafted laboratory procedures given to the students contained mistakes. Usually, the experiments were performed by a teaching assistant the week before the undergraduate lab met. However, the teaching assistant often did not complete the data analysis in time to verify that the laboratory equipment performed in a manner that was consistent with the assumptions made in the theory being evaluated. Typically, the undergraduate students informed the instructor that there was a problem with a cry of "none of my lab data makes any sense!" The instructor chose to embrace adversity and employ "learning from mistakes" as an instructional strategy for this engineering laboratory course.

Others have discussed learning from mistakes. Henry Petroski's book *To Engineer is Human: The Role of Failure in Successful Design*[1] suggests that more can be learned from failure than from success. In his book *Learning from Our Mistakes*[2], Henry Perkinson argued for a Darwinian learning theory that says we learn from our mistakes. Learning from mistakes has been employed in the educational fields of social studies[3,4] , business[5,6] , science[7-9], mathematics[10-13] , software engineering[14-17], drivers education[18], medicine[19], and other fields[20-22]. Learning from mistakes has been investigated by psychologists[23, 24] and neuroscientists[25]. For example, psychological researchers Needham[26] and Gick[27] have suggested that when individuals solve problems unsuccessfully before being given the correct answers, they are better at transferring their knowledge to analogous problems. It has also been suggested that focused attention on why the solutions were not correct is an important part of learning[28, 29]. The current work builds upon this research.

Mean Squeeze Lab

The primary learning objectives of the first experiment are for students to apply statistical methods to analyze data and to learn to organize written engineering reports. The first experiment is therefore designed such that the data collection procedures are simple and the results can be understood without extensive theoretical or analytical analysis. At this stage, it is not beneficial to burden the students with complex technical content when they need to focus on how to analyze and report data.

An example of such an experiment was called the Mean Squeeze Lab. This lab was derived from a colleague's research and development project with a manufacturer of drug delivery devices. A controlled-dosage device was being developed to deliver a single dose of liquid medicine into a child's mouth. The device was operated by manually squeezing a bulb. It was important to optimize the design so that the drug is delivered as quickly as possible but without gagging the infant. An important parameter is the force that a person applies to the device during squeezing. The students were asked to characterize the force applied to the controlled-dosage device by considering a population of college students (i.e., find the mean squeeze). For motivation, the students were told that their results would be used by the research project.

To collect the data, each student gripped a load cell that was approximately the same size and shape as the controlled dosage device, as shown in Figure 1. Each squeezed the load cell for 2 seconds to simulate delivering medicine with the device. Data from a number of squeezes by all students in a lab section were combined for statistical analysis. The lab handout specified that the students were to:

1. Compute and plot the histogram and frequency distribution for the lab section's data.
2. Compute the sample statistics (sample mean, sample variance, and standard deviation of the mean) for this data set.
3. Estimate the interval of values over which 95% of the measurement of the force should be expected to lie.
4. Estimate the true mean value of the force at 95% probability based on this finite data set.
5. Test the hypothesis that the force data is described by a normal distribution using the Chi-Squared test.

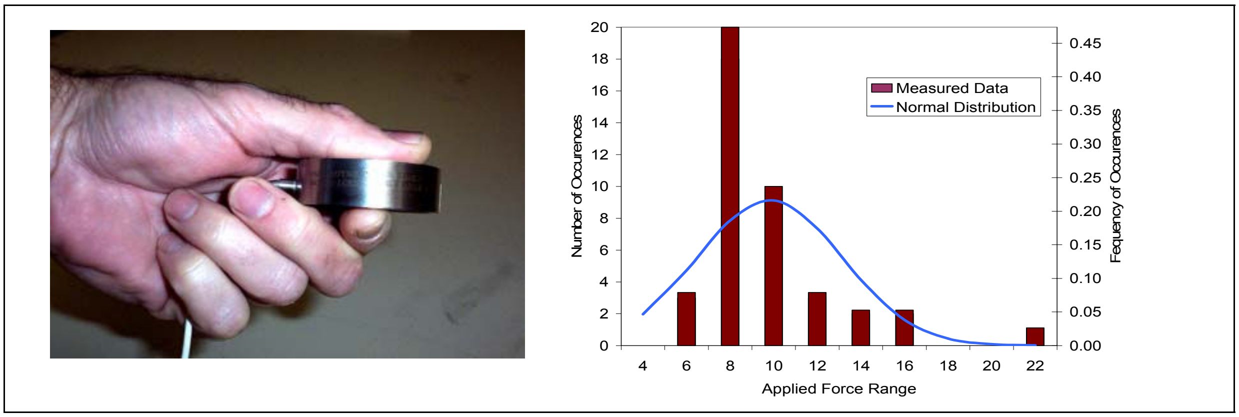

Figure 1. In the Mean Squeeze experiment, students characterize the force applied by squeezing a load cell between the thumb and fore finger (left). Statistical analysis of the data includes a histogram and comparison to the normal distribution (right).

A typical histogram of the squeeze force data from a section of 8 students is shown in Figure 1. The superimposed normal distribution has the same average and standard deviation as the data set. However, the data fails the Chi-Square test for normalcy – there is a 95% chance that it is not normally distributed. Unfortunately, most of the students performed the five data analysis steps in the order given on the lab handout. Because steps 2, 3 and 4 all assume that the data is normally distributed, their results appear to have no meaning. Students expressed frustration that they had wasted time calculating results that they could not report. The instructor used this opportunity to discuss the importance of critical thinking and about planning engineering procedures. The lesson learned is that the real world is not cookbook. Engineers must plan their own experimental and data analysis procedures.

Piston Kinematics Lab

Very accurate data is necessary for the course learning objective of identifying the strengths and limitations of a theoretical model as a predictor of real-world behavior. Therefore, it is desired that during at least one experiment each semester, the students gain experience with highly accurate, state-of-the-art measurement instrumentation. Fortunately, the department faculty members are active researchers and also dedicated to undergraduate education, and are willing to share some of their research equipment with the Measurements and Instrumentation course. One such device is a Brown and Sharpe Coordinate Measuring Machine (CMM).

In one CMM experiment, the students determined how piston displacement depends on crank angle in a single-cylinder internal combustion engine and compared their results to a theoretical equation. A schematic of a piston, connecting rod and crank is shown in Figure 2. Assuming that the crank and connecting rod have perfect pin connections, it can be shown by trigonometry that the distance between the crank axis and the piston pin axis (*s*) is given by

$$s = a \cos \theta + (L^2 - a^2 \sin^2 \theta)^{1/2} \tag{1}$$

when the connecting rod length (*L*) and the crank radius (*a*) are known. These values, and the distance from the piston pin axis to the top of the piston (*x*), are measured by the laboratory instructor and given to the students before lab.

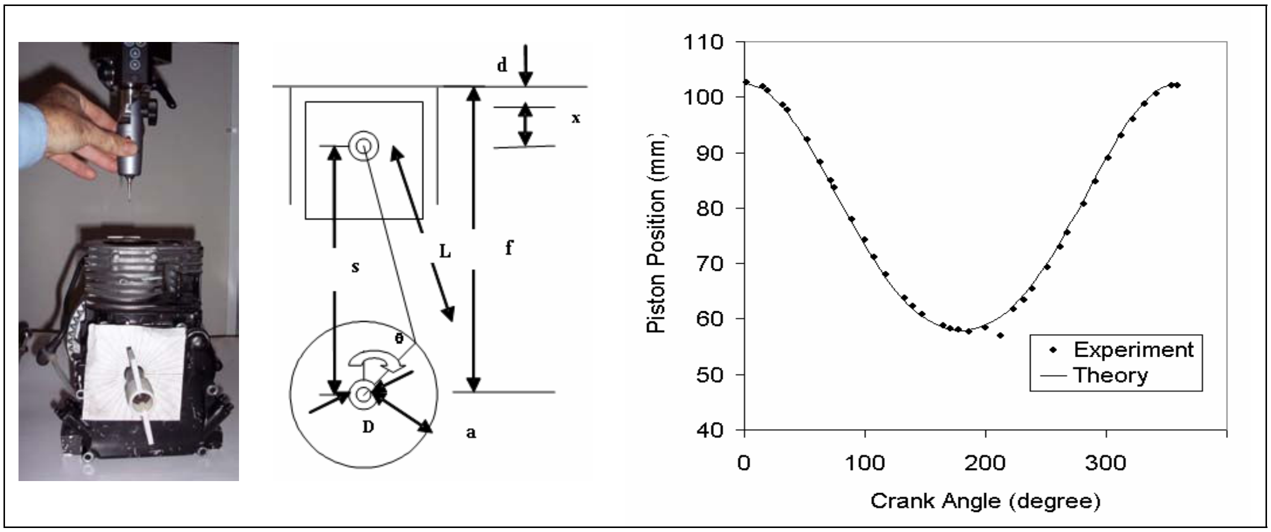

Figure 2. Using the touch trigger probe of a coordinate measuring machine (left), students determine the crank angle and the distance from the piston pin to the crank axis in a one cylinder engine. The experimental results are compared to a theoretical relationship derived from trigonometry (center). The students must explain why differences between theory and experiment (right) are not explained by instrument error.

During lab, the crank angle (θ) is measured with the CMM with the aid of a paddle attached to the crank shaft, as shown in Figure 2. Two points on the paddle are recorded and the CMM calculates a line through these points. Then, two points on the head of the cylinder are recorded and the CMM calculates this line. The CMM's feature relation function generates the angle of intersection between these lines, which is related to the crank angle.

It is not possible to directly measure the distance *s* while the engine is assembled. However, it is possible to measure the distance from the crank axis to the top of the piston (*d*) with the CMM. Subtracting the *x* from *d* allows one to determine *s*. During lab, the students work in pairs to measure *d* at different θ values from 0 to 360 degrees. They then calculate the value of *s* from the experimental data and compare it to the value of *s* from the theoretical equation. The results from a typical lab section are shown in Figure 2.

When the students first plotted their data as shown in Figure 2, they were impressed at how well the theory describes their results. However, when they calculated that the difference between the theoretical curve and their data exceeds the uncertainty of the CMM by a factor of 1000, they were forced to develop an explanation. When they looked carefully at their graph, they saw that for angles from 0 to 180 degrees, the experimental distance exceeded the theoretical, but for angles from 180 to 360, the theoretical distance exceeded the experimental. Why would this happen?

The students were then told that this particular engine was donated to the lab after being retired from the SAE mini-baha buggy. At this point, the engine was made available for further inspection and several students discovered that there was significant slop in the crack shaft bearing. When the piston was being pulled down by the crank, the slop made the distance s larger than expected. When the piston was being pulled up by the crank, the slop made the distance s smaller than expected. By requiring that the students compare the difference between experimental and theoretical results to the magnitude of the uncertainty in the experimental data, they are better able to establish relationships between measured data and underlying physical principles. The lesson learned is that engineers must be careful when comparing data to a theory. The data may be more correct than the theory.

Air Conditioner Thermodynamics Lab

The final two labs of the semester are more involved than the first three, each taking several weeks for the students to complete. This gives the students an opportunity to integrate and apply all they have learned in previous labs. In one such experiment, students were asked to perform a First Law energy balance on the Package Terminal Air Conditioner (PTAC) shown in Figure 3.

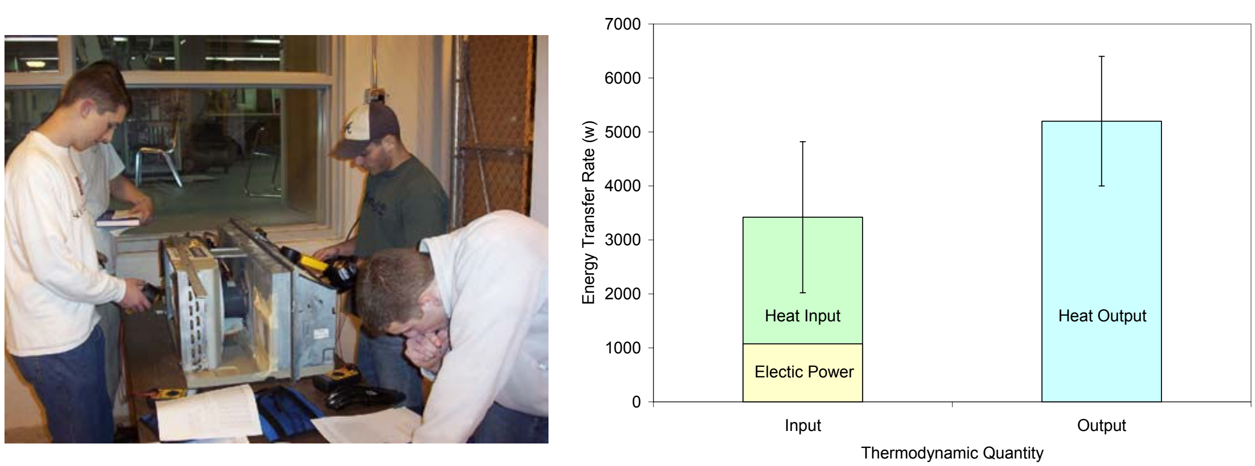

Figure 3. Students measured air speed, temperature and electrical current and voltage in the PTAC experiments (left). Their results suggested a violation of the First Law of Thermodynamics (right).

When the PTAC is considered as a control volume, the First Law of Thermodynamics can be written for the unit as

$$P + \dot{Q}_{in} - \dot{Q}_{out} - K\dot{E}_{net} = 0 \qquad (2)$$

where $\dot{Q}_{in}$ is the rate that heat is taken into the PTAC from the air, $\dot{Q}_{out}$ is the rate that heat is rejected from the PTAC, and $K\dot{E}_{net}$ represents the net change in kinetic energy of air moving through either side of the system. The students are given instruments to measure the dimensions of the input and output ducts of the PTAC, air velocity, temperature, electrical current and voltage. From the measurements, values of the terms in the First Law equation can be calculated. For example, the two heat terms were found from:

$$\dot{Q} = \rho \cdot v \cdot A \cdot c_p \cdot \Delta T \qquad (3)$$

where ρ is the density of air in the stream, v is the average velocity, A is the cross-sectional area of the flow stream, c_p is the specific heat, and ΔT is the temperature change of the air after it passes through the PTAC.

During the lab, students measure temperatures at different locations across the heating and cooling ducts with a type-K thermocouple. Air velocity is measured at each location with a handheld, propeller-based transducer. In our lab, a Fieldpiece LT17 digital multimeter with an integrated thermocouple input and a Fieldpiece AAV3 air velocity head are used for these measurements. The LT17 is also used to measure the electrical voltage applied to the PTAC, and is connected to a Fieldpiece ACH current clamp to measure the electrical current drawn during operation of the PTAC. Voltage and current data are combined to calculate the apparent power input for the unit. Specific heat and density values were not measured and had to be assumed. Students also had to determine the uncertainties in their measured data and in the calculated heat quantities.

Typical results are shown in Figure 3. The total input power found by the students is significantly less that the heat output. Due to the propagation of measurement uncertainties in the calculations, the energy quantities are associated with large uncertainties. Most students were quick to blame the differences between the input and output energies on the accuracy of the measurement devices in their reports. Likewise, they blamed the equipment for the poor quality of their results. After returning the graded reports, the instructor questioned the class about what other flow streams crossed the control volume besides air. Students recalled that a steady drip of cold water was observed coming off the evaporator. With the help of the instructor, they realized that the cold water leaving the PTAC represented a heat input to the unit that was not accounted for in the analysis. Furthermore, every student in the class had assumed values of density and specific heat for dry air (0%RH) in their calculations. This was also a mistake. The lesson learned was that while it may appear that unexpected results can be accounted for by uncertainty in the measurements, it still may not be correct.

Learning to Write by Rewriting Reports

The students' grades in the course are determined primarily from formal written laboratory reports. These reports typically include an abstract, introduction, procedure, results, discussion and conclusion section. Depending on the length of the lab, a page limit of between 4 and 6 pages is enforced. General guidelines for the lab reports are given to the students in writing, and specific content for each lab is discussed in class. However, the students are not given starter sentences or a list of questions to answer. The report format is therefore somewhat open-ended. It is very common for student achievement on the first laboratory report to be poor. From an instructional viewpoint, the objective is for continuous improvement in student achievement. The author therefore investigated the value of rewriting laboratory reports as an instructional strategy to improve technical writing skills. In three semesters (two falls and one spring) over a 6 semester period, the students were given the option to re-write their first lab report after it was graded. Their incentive was that their grade would be an average of the first and second drafts. In the other three semesters (two springs and one fall), the students were not given this option.

Figure 4 presents the average laboratory report grade in the class for each cohort of students for their first three laboratory experiments. As shown, when the performance on the first report was good, then the performance on the second and third reports were also good, regardless of whether or not the students were given the opportunity to rewrite their reports. However, when classes who performed poorly on the first report were given a chance to rewrite that report, the average score on subsequent reports was much higher than that achieved by students who were not given the rewrite opportunity.

From an instructor's viewpoint, re-grading a class full of reports may seem time-consuming and not worth the effort. However, in the author's opinion, grading an entire semester of poorly written reports takes much more time than grading one badly-written and many well-written reports. The report scores shown in Figure 4 indicate that the process of rewriting a graded lab report helps students learn from their mistakes. This suggests that having students rewrite reports early in the semester improves student learning thereafter. The added benefit is a reduction in the total amount of time during the semester that the instructor must spend on grading. It is a win-win situation.

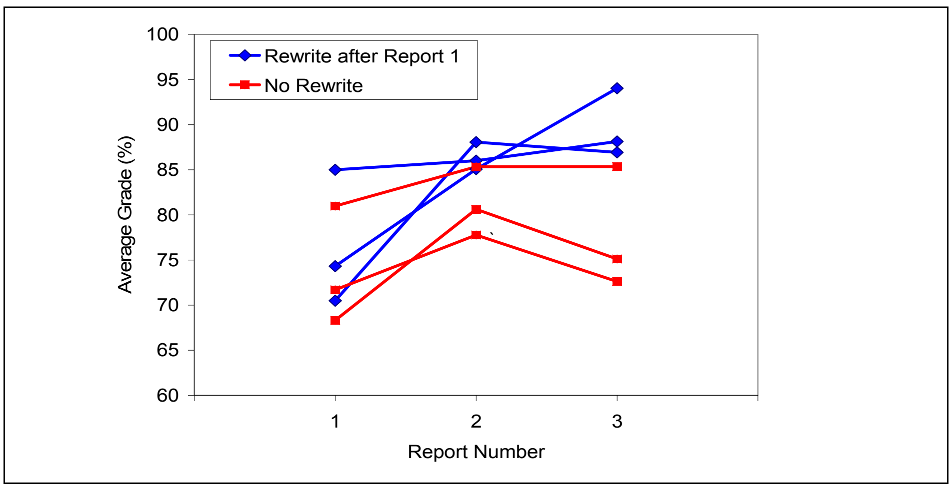

Figure 4. When a class of students is given the opportunity to rewrite their first laboratory report (blue diamonds), their performance on subsequent reports typically exceeds the performance of students who did not have this opportunity (red squares).

Conclusion

The instructor's challenge of maintaining the learning value of laboratory courses is the time and creativity it requires to create new and interesting experiments for the students. Time or resource limitations can result in students conducting experiments that produce unexpected results. If "learning by mistakes" is used as a guiding instructional strategy, then students can and should be expected to continually and purposefully find problems with their measurements and assumptions. Students can then feel compelled to make engineering judgments or additional measurements. Experience with this approach in our mechanical engineering Measurements and Instrumentation course indicates that experiences like this can help students develop a sense of pride and confidence in the results. It is suggested that the critical thinking skills developed in this way can be more easily transferred to other situations.

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