Scaffold Approach to Teaching Experimentation

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Introduction

In the real world, engineers are often faced with the task of designing and conducting experiments to evaluate the performance of products, systems, or processes. Realizing the importance of this knowledge on how to construct and analyze meaningful experiments, many mechanical engineering curriculums have incorporated a required undergraduate course dedicated to teaching "engineering experimentation". The course we have devised to meet this need has the following four learning objectives: (1) Given an experimental setup, know how to select an appropriate sensor based on characteristics and error (2) Given measurement results, be able to interpret measurements taken and experimental results with regard to sources of uncertainty, (3) Given a general product, system, or process, be able to formulate a testable hypothesis, and (4) Know how to utilize statistical experimental design to rigorously test a hypothesis. Each of these learning objectives build upon one another, thus a scaffold approach is implemented to guide student learning [1-3].

Within this work we aim to provide the reader with documentation of our scaffold approach and metrics to evaluate its effectiveness with respect to student learning. In particular we detail how our students begin with learning the fundamentals measurement, such as force, strain, motion, pressure, and temperature. They learn not only the theory but also construct experiments and work in teams. Students then report on metrics such as accuracy, dispersion, linearity, et cetera by means of short communications in the form of 2-page written lab reports. These reports serve as summative assessments for the course and provide feedback to the students for improvements within all aspects of experimentation: methods, analytics, reporting results, and interpretation. Within this work we present a means to track the progression of the students' learning with this scaffold approach through the longitudinal evaluation of the summative assessments. Each assessment is based on the same rubric, which the students are given at the beginning of the course. Lastly, a final student questionnaire is given to analyze if the learning objectives are perceived achieved. Knowing the compounding factors involved in obtaining successful student outcomes when working in groups [4], we utilize the fact that within the scaffold approach that the overriding factor of proper level of instructor guidance can be enforced [5]. Thus the analyses presented on our scaffold approach for teaching engineering experimentation are considered valid.

Methods

A primary course goal was to improve student abilities in designing and executing experiments, as well as in the effective communication of their experimental process and thinking. Prior implementations of this course have opted to pursue a greater number of experiments (more than the number detailed here) with consistent guidance and reduced report requirements (to facilitate the completion of many experimentation experiences in the semester time frame). This construct argues that student learning is strongly dependant on the number of experiences that they are exposed to, and that guidance at every point should be given to ensure enough experiences can be completed in the class time frame. Conversely, one instructor recently implemented a major re-thinking of the course and opted opted to pursue only two major experiments/reports with minimal guidance given. This construct argues that student learning is strongly enhanced when students are challenged to discern and develop every aspect of the experimental process primarily on their own. Based on these relative two extremes, the instructors (authors) opted to explore if course goals could instead be achieved through structured levels of guidance using a scaffolded learning approach. In developing a scaffolding approach for laboratory experiments, instructors considered key aspects of the experience and how each aspect could be gradually incremented toward a final goal. Overall categories for scaffolding included guidance provided, experimental complexity, analysis complexity, and critical thinking. Aspects of scaffolding in each category are summarized in Tables 1-4 and subsequently detailed.

In the course design detailed here, six laboratory experiments were completed over the course of a semester, each requiring a two page experiment report. Laboratory groups consisted of two or three students. Reports followed standard academic structures and consisted of the following main sections: Introduction, Methods, Results, Tables and Plots, Discussion, Conclusions, and References. Each section was independently scored based on a rubric provided to the students at the course initiation and for each report detailed feedback was given for each section. Overall quality of language and formatting was also scored and given feedback. Note that, for the six laboratory experiments the structure and rubric of the two page report remained consistent.

Table 1: Scaffolding Guidance Provided

Experiment	Word Count	Report Guidance	Initialization Guidance	Check Given
1: Load Cell	580	14 items	yes	Generate testing table of 5 (minimum) excitation voltages and 4 (minimum) applied loads.
2: Strain Gage	530	8 items	yes	Calculate applied weight at which beam will deform given material and beam geometry.
3: Pressure	300	12 items	yes	Calculate maximum manometer height difference which can be applied given sensor data and fluid properties.
4: Thermistor	210	6 items	no	

5: Accelerometer	330	6 items	no	
6: Grip Test	170	5 items	no	

For each experiment a Laboratory Guide sheet was given which might include overall purpose of experiment, sensor details, equipment to be used, minimum requirements for data collection, and other notes for the experiment or report. Initial guide sheets were roughly two pages in length and final guide sheets were roughly half a page. Specific word counts for each guide sheet (Table 1) demonstrate the incremental reduction in the amount of written guidance given for each experiment.

Report guidance (Table 1) refers to the number of items that students were explicitly told to include in their reports. Not only were the number of specified report items decreased throughout the course but the way in which the items were presented was made increasingly general. For example only in the first experiment were the items bulleted and broken down based on the section of the report in which they should appear. Experiments 2 and 3 had bulleted but otherwise unorganized lists and later experiments gave few to no bullet points, instead describing items in paragraph form.

Initialization guidance and the associated check given (Table 1) refers to specific prompts which guided the students on the first step in their experiment. Typically this involved taking the time to perform a calculation that would ensure that sensors or other lab materials would not be damaged. However, this also served to provide students who were unsure how to begin, a starting point and a construct for what the bounds of the experiment would be.

Table 2: Scaffolding Experimental Complexity

Experiment	Focus	Variables	Other aspects
1: Load Cell	Accuracy and error	1 (load)	Collecting 1 signal of data using a DAQ board
2: Strain Gage	Accuracy and error	2 (load,distance)	Collecting data using two different devices
3: Pressure	Calibration with short test	1 (height)	Collecting data following a specific order (hysteresis impact)
4: Thermistor	Calibration with short test	1 (temperature)	Collecting data following a specific order and given a limited resource (ice)
5: Accelerometer	Calibration and test	1 (fixture)	Collecting 3 signals of data using a DAQ board

6: Grip Test	Calibration and test	3 (mixed)	Students determined their own factors and levels to examine

For each experiment the focus of the work to be completed was expanded (Table 2). Experiments 1 and 2 focused only on the recording of multiple measurements with the goal of performing accuracy and error calculations. Experiments 3 and 4 structured the recording of multiple measurements around a static calibration process. In addition to the calibration processes, roughly ten test measurements were collected but this represented a small portion of the experimental time. Experiments 5 and 6 expected students to be proficient in quickly performing a calibration process without explicit guidance with only a short amount of time dedicated to this effort. In these experiments the focus was on extensive testing.

It was desired, though not fully achieved, to scaffold the number of variables that each experiment considered (Table 2), yet many experiments only lent to manipulation of one variable. However, this highlights that when developing a plan for scaffolding it can be desirable not to increase the challenge level of every aspect for each new assignment. Alternatively, instructors can increase and then reduce challenge level of a specific aspect in order to increase the challenge of another aspect without overwhelming the students. Typically the final step in such a process is an assignment that incorporates increased complexity across multiple aspects but where students have performed assignments in which each aspect individually presented the same level of challenge.

Table 2 also details other aspects of experimental complexity that increased the challenge level of the experiments. One aspect of scaffolding was initial use of a DAQ system to record a single signal of data and later using the same system with modifications to record multiple signals of data. Another aspect of scaffolding was that measurements in early experiments could be recorded without an overall plan for the order in which they should occur. Experiment 3 introduced the requirement that the order in which data was collected must be decided in advance as data collected out of order would not reflect the desired impact of hysteresis. Experiment 4 built on this requirement as students needed to decide if they wished to incrementally increase their temperatures (with a hot plate) or incrementally decrease them (with ice). Additionally students had a limited resource to consider in their protocol plans (amount of ice) which would only allow them to complete the process one time. These manipulations forced students to incrementally develop their skills in planning an experimental procedure.

Table 3: Scaffolding Analysis Complexity

Experiment	Signal conversion	Statistical measures	Calibration Calculation	Error Calculation
1: Load Cell	Voltage to mass	Mean, STD	none	Absolute, Percent theoretical
2: Strain Gage	Resistance to strain, direct strain	Mean, STD	none	Absolute, Percent theoretical
3: Pressure	Voltage to pressure	Max error	Linear	Percent hysteresis, Percent linearity
4: Thermistor	Resistance to temperature	Max error	Linear and logarithmic	Percent theoretical, Percent linearity
5: Accelerometer	Voltage to acceleration	Mean, STD	Linear (3 axis)	
6: Grip Test	No units to mass	ANOVA significance and power	Linear	

Statistical measures (Table 3) were kept relatively simple while calculation of calibration equation and types of error were increased. However, in Experiment 6 the introduction of much more complex statistical methods (ANOVA) and associated software was accompanied by complexity reductions in other areas.

Calibration calculations (equations for converting between recorded data units and experimental units) were initially given to students to use in their signal conversions (Table 3). Later, concepts of sensitivity and zero bias were introduced in which students were expected to generate their own linear calibrations. Finally students were asked to solve systems of equations to fit data to a given logarithmic calibration equation and also to calibrate multiple independent signals before combining to generate a single outcome measure.

Table 4: Scaffolding Critical Thinking

Experiment	Key tasks organized according to Bloom's Taxonomy Level
1: Load Cell	Apply: Use given calibration equation to convert from voltage to mass Apply: Solve for statistical and error measures for each data set Analyze: Compare calculated data to expected values Evaluate: Support a value for excitation voltage to use in future experiments Evaluate: Critique possible sources of error and limitations Create: Devise an experimental method
2: Strain Gage	Apply: Use given calibration equation to convert from resistance to strain Apply: Use theory of bending stress and stress-strain relationships to find theoretical strain Analyze: Compare strain measurements collected using resistance and strain indicator to theoretical strain Evaluate: Select and support the method of strain measurement you find best Evaluate: Critique possible sources of error and limitations Create: Devise an experimental method
3: Pressure	Apply: Use theory of manometers and known values to find theoretical pressure Apply: Solve for a linear trendline that relates voltage to pressure (calibration) Apply: Solve for various aspects of error (absolute and percent) Analyze: Compare calibration line to subsequent collected data points Evaluate: Discuss observed trends and propose technical reasons for the trends Evaluate: Critique possible sources of error and limitations Create: Devise an experimental method
4: Thermistor	Apply: Solve for a linear trendline and a logarithmic trendline that relates resistance to temperature (calibration) Analyze: Compare error of a two part linear calibration curve to error of a logarithmic calibration curve Evaluate: Select the calibration curve you find best Evaluate: Propose a temperature range for which the sensor can be used Evaluate: Critique possible sources of error and limitations Create: Devise an experimental method
5: Accelerometer	Apply: Solve for a linear trendline that relates voltage to mass (calibration) Apply: Use knowledge of DAQ code to execute a collection of multiple signals Analyze: Relate expected acceleration at each part of drop test (holding, free fall, impact, resting) to outcomes in terms of gravity

	Analyze: Compare the repeatability of different drop test fixtures Evaluate: Judge the data that represents impact and how best to report Evaluate: Select and defend the drop fixture you find best/most repeatable Evaluate: Critique possible sources of error and limitations Create: Devise an experimental method
6: Grip Test	Apply: Use design of experiments concepts to select appropriate factors and levels Apply: Solve for a linear trendline that relates voltage to mass (calibration) Apply: Use SPSS software to apply ANOVA model to collected data Analyze: Compare significance and power values for each factor to distinguish significant factors Evaluate: Weigh relative impact of each factor Evaluate: Critique reasons that factors were significant or non-significant Evaluate: Critique possible sources of error and limitations Create: Devise an experimental method

In regards to scaffolding of critical thinking and levels of Bloom's Taxonomy one approach would be to incrementally add higher level tasks as projects progressed. However, engineering experimentation courses offer excellent opportunities, from the very start, to develop student thinking and learning abilities across a range of levels as outlined in the Bloom's Taxonomy (Table 4).

A characteristic objective in experimentation classes is the development of student ability to formulate clear and appropriate hypotheses. Indeed, this task was addressed in every experiment and report of the course. A unique approach in this course was that students were encouraged to consider if a hypothesis or a deliverable was more appropriate in approaching/reporting their work. Instructors propose that generating a deliverable statement pushes students to think critically about what will be gained or known as a result of the experiment. In addition, deliverables are likely more pertinent to the majority of experimental work performed in industry, as well as the types of experiments performed in an undergraduate curriculum.

Other tasks were also consistent throughout the experiments. For example, every experiment required students to apply their understanding of sensors to convert between experimental units and physical units of interest. At the analyze level, students were typically asked to make comparisons between experimental and theoretical outcomes, different methods of collecting data, different types of calibration curves, and other similar tasks. Higher level tasks were also expected to be addressed from the first experiment onward. Students were asked in each report to evaluate possible sources of error, experimental limitations, and possible improvements for future experiments. However, because these tasks require greater critical thinking, repeated practice and instructor feedback was required before students demonstrated proficiency.

Similarly, students were asked in each experiment to devise their experimental method. In Bloom's Taxonomy, tasks involving generation of new ideas or products are considered to require higher level thinking. Thus, as detailed above, this task was presented to students for each experiment with scaffolding approaches to gradually remove the amount of assistance given in attaining this higher level goal. Overall, though a range of Bloom's Taxonomy levels were included in each experiment and report, instructors endeavored to continually shift towards greater focus on, and number of, higher level tasks as the experiments progressed.

Results

Thirty-one students (22 male and 9 female) were instructed using the described scaffold approach. The students were a mix of both junior and senior undergraduates in Mechanical Engineering and consisted of 2 groups of two students and 9 groups of three students. While two instructors did teach different sections of the course, the results have been lumped together since the instructor materials, scaffolding exercises, and experiments, along with the order in which they were performed, were the same for both.

To examine the students' learning during scaffolding, the scores of each laboratory report were recorded and a longitudinal study was performed. As seen in Figure 1, this quantitative metric started at a mean of approximately 86% and steadily increased on average to a final mean of approximately 93%. Repeated measures ANOVA was run on the laboratory report scores (within factor of laboratory report number) using SPSS 22 and significance was defined as $p<0.05$. Mauchly's test showed that the condition of sphericity was met. Laboratory report number was a significant factor with $p=0.017$. Subsequent pairwise comparisons with Bonferroni correction showed a significant increase between Lab 1 and Lab 6 ($p=0.011$). This suggests that significant improvement in score was attained despite the use of a scaffold approach that increased challenge level and provided less and less guidance over time. Recall also that the rubric for scoring remained the same for all laboratory reports. Additionally, it is important to observe that the dispersion, or standard deviation, does not increase but instead decreases from approximately from 6.5% to 4.3%.

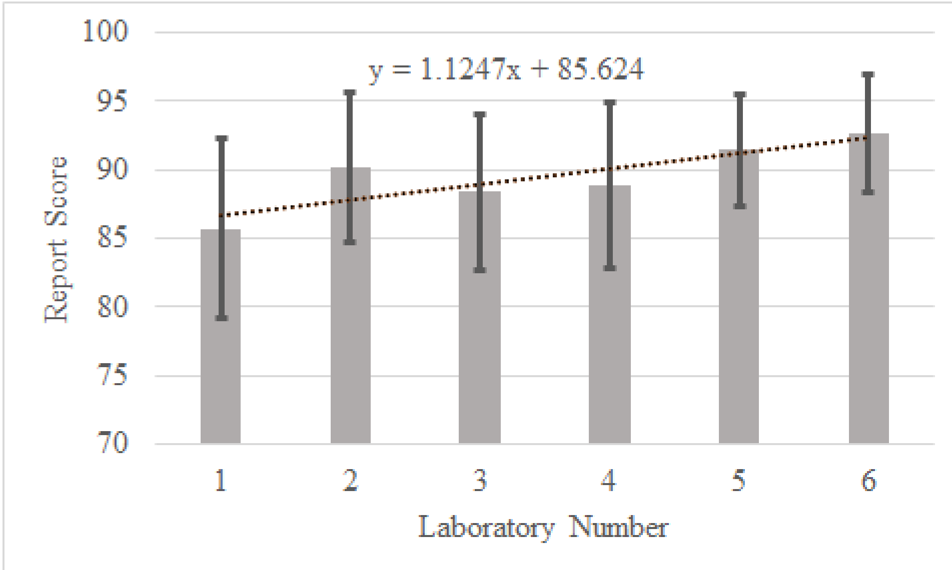

Figure 1. Longitudinal Assessment of Laboratory Reports

While summative assessments can provide much information as to what level the students are learning, formative assessments often provide additional insights into areas such as perceived strengths or weaknesses. Using our University's standard evaluation of teaching questionnaires, all 31 students completed an anonymous survey. The quantitative results based on Likert type questions are shown in Figure 2. Questions 1-6 are considered to gauge the students' perception about the scaffold teaching method since both instructors used this method. Looking at the divergent plot in Figure 2, a favorable bias is seen. Lumping these questions together, a Likert scale is generated to verify this bias. The results yield a mean of 4.7/5 and a standard deviation of 0.5. For comparison, the mean of the same set of questions in other courses within our Mechanical Engineering department is 4.2 (N~1100: Note standard deviation is unknown). Thus, not only is there a perceived favorable bias by the students but it appears to be a method which the students prefer over other teaching methods.

Evaluating the survey further, questions 7-11 in Figure 2 are considered to gauge the students' perception of their learning. Performing a similar analysis as above, a slightly weaker favorable bias is observed. Performing a Likert scale, the results yield a mean of 4.5/5 and a standard deviation of 0.6. The comparison to the same set of questions within our Mechanical Engineering department yields a mean of 4.2, yielding an indication that the students also perceive their learning to be improved with this method over other teaching methods.

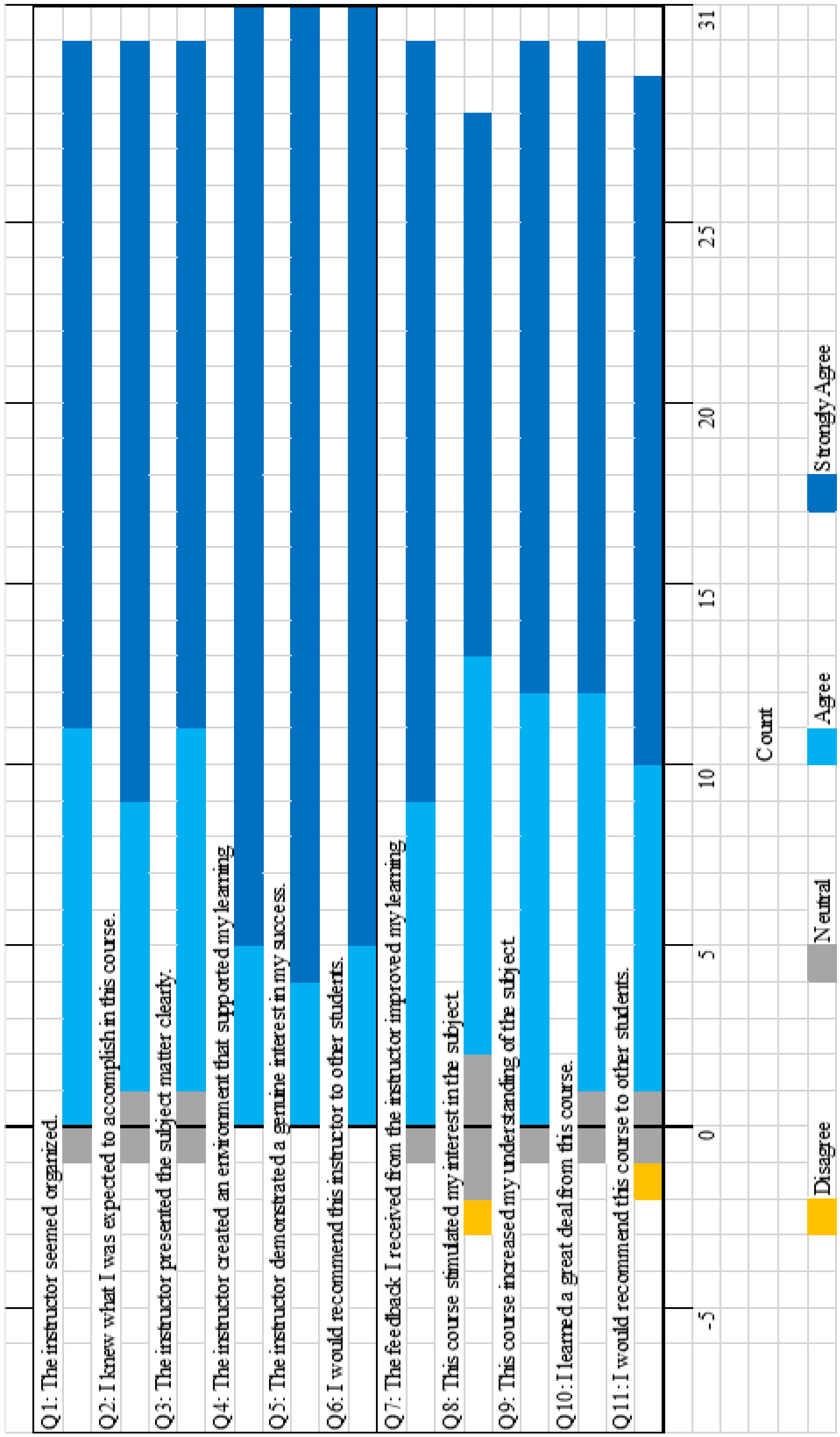

Figure 2. Student Survey of the Course

Discussion and Conclusion

A scaffolding approach to teaching is often employed and considered to generate effective progress in learning outcomes. In applying this approach to an engineering experimentation course the instructors considered four primary categories: guidance provided, experimental complexity, analysis complexity, and critical thinking. In each category specific aspects were identified and a plan developed to systematically increase complexity and level of challenge throughout the course. As detailed in this process, instructors may often need to consider when significant increases in complexity in one category should be offset by smaller increases, or reductions, in other categories. This approach was then assessed using laboratory report scores and student survey evaluations.

The scaffolding approach utilized by the authors resulted in a trend of increasing total laboratory report score despite increasing complexity across the four categories considered. Specifically, scores in Lab 6 were significantly higher than scores in Lab 1. In addition, variability across groups decreased over time, suggesting that this approach was effective for both high performing and lower performing groups. This is likely due to the fact that students had sufficient number of experiments over which to refine their approach. In addition, report structure and expectations were maintained consistent across all experiments, likely allowing students to identify and address areas of weakness or specific points that were missed.

The scaffolding approach also appears to result in strongly positive student evaluations related to understanding of expectations, overall clarity, supportive learning environment, quality of feedback, increased interest, and increased understanding. Specifically these ratings were much higher as compared to department level means.

Though this approach appears to have positive outcomes it is unknown if alternate approaches (as briefly summarized in the Methods section) could be significantly more effective. Future assessment of this strategy will focus on exploiting the variety of approaches employed by the many instructors of this course. Through collaboration with other instructors a set of consistent assessment methods could be applied to all students (at minimum pre and post course) and the outcomes across approaches compared.

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