

Enhancing Inquiry Skills in Engineering through a University-School District Partnership

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Abstract – The Partnership for Student Success in Science is a collaborative educational project between San José State University and nine Silicon Valley area school districts. Engineering faculty from San José State University (SJSU) are participating in the project to both provide content knowledge for teacher professional development and to enhance undergraduate instruction in the SJSU College of Engineering through enriched pedagogy. Strategies for incorporating inquiry-based learning into the SJSU undergraduate and graduate engineering curricula have been explored in both lecture and lab courses. Inquiry lab periods have been included in the Aerodynamics course. Similarly, in the Biochemical Engineering Laboratory course, students are given the opportunity to answer a question of their choice through literature review and experimentation. Inquiry-based learning has also been incorporated in lecture and laboratory courses in the Civil Engineering program. An informal assessment of these techniques has facilitated their improvement in execution and shown their effectiveness in teaching students difficult engineering concepts.

Index Terms - Inquiry-based experiment, Biochemical Engineering, Aerodynamics, Structural mechanics, K-20 education.

BACKGROUND

In 2003, the Partnership for Student Success in Science (PS³) initiated a five-year program funded by the National Science Foundation's Math/Science Partnership initiative to improve middle school science education. The partnership combines nine local middle school districts in California's Silicon Valley, the Colleges of Engineering and Education from San José State University, and two industry sponsors. The Partnership is a strong believer in inquiry-based learning and builds upon a previous project with many of the same school districts that involved K-5 educators. Four faculty members from the College of Engineering work with local middle schools in strengthening the science content knowledge of the middle school teachers. Engineering faculty enhance middle school educator's knowledge by delivering science and

engineering content in week-long summer intensive workshops and short professional development sessions during the school year at district school sites. These same faculty members enhance their own pedagogical knowledge by participating in additional professional development training offered by K-12 science education specialists. The professional development workshops have exposed the four engineering professors to some of the excellent research on how people learn that has driven many pedagogical innovations in K-12 education. The professors are experimenting with the K-12 inquiry pedagogies by adapting them to their engineering classes. Anagnos and McMullin used a number of these same strategies in the development of inquiry-based educational modules in earthquake engineering [1]. To disseminate what they are learning, the authors have offered two workshops on inquiry to other members of the College of Engineering faculty.

A review of research on student learning by the National Research Council indicates that mechanisms to facilitate active learning strategies for students are needed at all levels of instruction [2]. Specifically, students must engage their understanding and address preconceptions, which are often misconceptions, for effective science learning. Unless addressed, misconceptions persist and restrict deeper learning. Building on a solid foundation of factual knowledge, students can develop their comprehension of science and engineering concepts in the context of real-world questions and problems. Inquiry-based learning is an effective method to help students construct a framework of understanding that can then be applied to the types of questions that they will encounter after graduation.

When students are involved in the development and delivery of their own learning, they can guide and pace their learning taking into account on their prerequisite knowledge and comfort with the topic. Inquiry-based activities let students adjust the questions they want to explore, the level of complexity of the investigation, the pacing, and the approach they take. In inquiry-based learning, the student and the teacher share the responsibility for the development and delivery of the learning. Du *et al.* demonstrate how inquiry-based learning can be represented by an "inquiry continuum" on which the student-faculty responsibilities vary [3]. On the

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left end of the continuum are lectures, demonstrations, and traditional “cookbook” laboratories in which the professor is responsible for all of the development and delivery. On the right end is student-designed inquiry in which a student is responsible for the complete experimental design. Structured labs and challenge labs are found in the middle of the continuum and require varying degrees of involvement by the instructor and the student.

Inquiry-based learning can be incorporated into both lecture and lab courses. The “interactive lecture” with collaborative inquiry questions interspersed at regular periods has been shown to significantly enhance student learning as compared with the traditional lecture format class. In laboratory courses, while traditional cookbook laboratory experiments expose students to experimental methods, they do not hone students’ critical thinking skills and therefore are not effective in helping students master several important skills that will be necessary for them once they have graduated from college. Specifically, the ability to design an experiment and justify the significance of an experiment, cannot be learned through simply following a step-by-step procedure.

LECTURE INQUIRY ACTIVITIES

PS³ faculty experimented with “interactive lectures” in a structural mechanics course. Mechanics of Materials (CE 112) is a one semester, three hour per week course taken by students in civil, mechanical, and aerospace engineering. Most of the students are juniors, though a few graduate students also take the course. Enrollments are 25 to 40 students per class. Traditionally, this class is taught in a lecture format, with the lectures introducing theory that is illustrated with example problems solved by the professor at the blackboard. Students busily copy notes, but don’t have time to engage with the example problems. A common complaint from students when they try to solve the homework problems is “but it looked so easy when you solved it on the board.”

Inquiry was introduced into the lectures by requiring students to attempt the problems before the professor solved them in front of the class. A lecture would begin with a relatively short explanation of the theoretical concept and its application. Before solving an example problem, the professor would ask the class to break into groups of two to four students and apply the concepts to a problem. While they were working, she would walk around the classroom and help groups get started or answer questions when they got stuck. Because the students were working in cooperative groups, students were also helping each other with roadblocks and challenging concepts. To ensure that all students remained engaged, the professor provided a second problem to those groups that solved the problem quickly. After five to ten minutes, even if students were not finished, the professor would complete the solution on the board. If it appeared that most of the students understood some aspect of the problem, for example the free body diagram, then the professor did not spend much time on that step. Students were included in the

board solution by asking them, “What did you do first?” and, “Why?” followed by, “What did you do next?”

The impact on the class was immediately obvious. If one student proposed an incorrect step, other students were quick to note that they had done it differently. Students continually asked questions as steps were shown on the board, so there was a lot of chatter in the room. Students were very engaged in the problem because they wanted to understand why their solutions didn’t lead to the right answer. The amount and type of interaction was different than the more traditional approach in which the professor solves the example without asking the students to do it first. In the traditional case, even if the professor asks the students to participate in the solution, only a few students are engaged and the rest are copying the solution down under the assumption that they’ll figure it out later.

Faculty also experimented with the use of assessment probes to uncover misconceptions that might inhibit learning. Before a theoretical concept was introduced, students were posed a question with three possible answers. Students were asked to write their answers along with a justification on a 3” x 5” post-it. Students then created a histogram on the wall by posting their answers in three labeled columns, making it immediately obvious if the class had a correct understanding of the concept. If the post-its were not all in one column, the faculty member could take a quick look at the justifications to identify the misconceptions. Students became engaged because they wanted to know why everyone didn’t think the way they did, and of course, they wanted to know the correct answer. One follow up activity is to have a discussion in which students explain their reasoning, and even allow students to move their post-its. Another approach is to adjust the theory lecture that follows to address the misconceptions.

As a formative assessment, students were asked to anonymously respond to the questions:

- How do you feel about having time in class to work in small groups on problems before they are done on the board as examples?
- Does it help you understand the examples better?

Nineteen students responded very positively, three responded positively with qualifications, and two were negative. The qualifications were issues related to who was in a group, the amount of time group work takes, and it being easier to follow an example. The challenge of struggling through unfamiliar problems created a strong bond between the students. The students were very supportive of one another and very talkative in class. The end of the year ratings for the class were some of the highest the professor has seen, with comments like “best engineering class ever,” and “very effective.” Students earned the full range of grades from A to F, so inquiry is not the solution to all learning problems. However, the inquiry activities were effective in creating enthusiasm and interest in the subject.

AERODYNAMICS LABORATORY

Aerodynamics (AE162) is a one-semester, junior level, lecture /laboratory course. A typical enrollment is 25 students. It is an elective for mechanical engineering and required for

aerospace engineering majors. The lecture is 3 hours per week while the laboratory is by arrangement and it involves five experiments. Students are asked to design their experiments beforehand and their design must be instructor-approved before they are allowed to do the lab. They also take a pre-lab test on the theory concepts pertaining to the lab. They work in teams of three or four students and write full laboratory reports for each experiment.

Among other objectives, the course aims at satisfying ABET Engineering Criteria 2000 and in particular Criterion 3b, which states that engineering graduates must have “*an ability to design and conduct experiments, as well as to analyze and interpret data*”. While the ability to conduct experiments, as well as the ability to analyze and interpret data has been addressed by traditional laboratory courses, the ability to design an experiment is a new challenge for both engineering educators and students. To meet this challenge, a general process as summarized in Table 1, was developed to help students design their experiments in any lab. This process is suitable for a level 5 (Student-Directed Inquiry) on the Inquiry Continuum [3].

TABLE 1
PROCESS FOR DESIGN OF EXPERIMENT

Step	Task
1	Discuss the importance and practical applications of the experiment
2	Given the goal(s) of an experiment, define the objectives
3	Research relevant theory and previously published data from similar experiments
4	Select the dependent and independent variable(s) to be measured
5	Select appropriate methods for measuring selected variables
6	Choose appropriate equipment and instrumentation
7	Sketch the experimental setup and describe a step-by-step procedure for performing the experiment
8	Select the proper range of the independent variable(s)
9	Determine an appropriate number of data points needed for each type of measurement

Following this process students:

1. Discuss the importance and practical applications of the experiment: For example *...flow visualization is important because it helps us understand the flow patterns around bodies of various shapes. This understanding is necessary to improve the design of aerospace, marine, and even land vehicles that travel at high speeds.*

2. Given the goal(s) of an experiment, define the objectives: While the goal is general (ex. *study the flow quality in the wind tunnel*), the objectives need to be specific and measurable (ex. *check the flow uniformity at the entrance and exit of the wind tunnel test section*).

3. Research any relevant theory and previously published data from similar experiments: Performing computer simulations may also be part of this research, assuming that appropriate software is available. The purpose of this step is to have a general idea about what to expect from the experiment.

4. Select the dependent and independent variable(s) to be measured: For example, in an experiment to study the performance of an airfoil, the independent variables may be the airspeed in the wind tunnel test section (or more correctly the Reynolds number that corresponds to this speed) and the angle of attack of the airfoil with respect to the free-stream flow. The dependent variables may be the airfoil pressure distribution, the lift and the drag.

5. Select appropriate methods for measuring these variables: For example, in the airfoil experiment, the lift can be found using (a) integration of measured pressure distributions on the surface of the airfoil and (b) direct lift measurements from a dynamometer. Students compare the results from each method with published data and computer simulations, and discuss the accuracy of each method.

6. Choose appropriate equipment and instrumentation: Using the same experiment (airfoil performance) as an example again, the surface pressure distribution can be measured using (a) pressure sensors and (b) a multi-tube manometer. Students use both methods for each measurement, compare the results from each method with published data and computer simulations, and discuss the accuracy of each method.

7. Sketch the experimental setup and describe a step-by-step procedure for performing the experiment: This is a very important step because experiments are often designed to be repeated with different test specimens.

8. Select the proper range of the independent variable(s): Although on the surface this seems like a straightforward step, students often use a limited range of independent variables and they are unable to compare their results with published data. For example, considering the range of angle-of-attack for the airfoil, they may get data for five or six angles in the range of 0 – 10 degrees. Without any data for negative angles of attack they cannot capture the zero-lift angle of the airfoil. Moreover, without any data for angles greater than 10 degrees they cannot capture the stalling angle-of-attack and the maximum lift coefficient of the airfoil. If students do not select the proper range of angles they will have to revisit the lab and re-run the experiment to collect additional data for comparisons with theory and published data.

9. Determine an appropriate number of data points needed for each type of measurement: The number of data points needed for each type of measurement depends on the kind of relationship between the variables involved. For example, to capture the slope in the linear portion of the lift curve two points may suffice and a third one may be taken to confirm the

linear shape. In the stall region, however, where the lift varies in a highly non-linear fashion with angle-of-attack, students need to select additional points to capture the shape of the curve and the post-stall behavior of the airfoil.

This process of experimental design was first implemented in the spring semester of 2005 and it is used again this semester (Spring 2006). Although students are still having difficulties with some of the steps, this process has yielded significant improvements, which become evident in their laboratory reports. In particular, they are usually more engaged in the lab because they better understand the practical applications of each experiment. They develop inquiry skills as they pose questions in regards to what they need to measure in each experiment. The answers to these questions are of course, the objectives of the experiment. They are better prepared in the lab and collect meaningful data. They enhance their lifelong learning (research) skills. Finally, their reports have improved dramatically, especially when it comes to results and discussion.

BIOCHEMICAL ENGINEERING LABORATORY

The Biochemical Engineering Laboratory Course (CHE 194) is a one semester, 5 hour per week course to provide hands-on learning to senior chemical engineering students interested in entering the biotechnology industry [4, 5]. The course is centered upon experiments with green fluorescent protein (GFPuv)[6], including a subcloning experiment to transfer the GFPuv gene to a high expression plasmid, fermentation, chromatography, ultrafiltration, and enzyme kinetics. The course syllabus lists 47 learning objectives that identify specific skills for measurement and analysis to be developed by the students in the course. There are various techniques that the students need to learn before they are prepared to tackle their own experimental design, and the first seven lab sessions prepare them with these skills. For example the labs emphasize basic sterile technique, pipetting, measurement of total protein using a Bradford assay, loading a chromatography column and running a Fast Performance Liquid Chromatography (FPLC) system, and others. While students in a biology program would learn these in their core courses, chemical engineering students are not exposed to them until CHE 194.

Two of the lab sessions are dedicated for students to design and implement an experiment of their own choice, which was inspired by professional development sessions provided by the PS³ teacher-training team. At these sessions, inquiry activities were included that involved a brief demonstration followed by the opportunity for the teachers to select of a question about the phenomenon that was demonstrated. The instructor then used post-it notes to help the participants organize their inquiry question by category of "dependent variable", "independent variable" and constants. As in the PS³ events, students in the CHE 194 course work in pairs, groups of three or they may also work alone. The grading rubric is slightly modified for students working alone as compared with working in a team. Namely, the scope of a

team-based experiment is larger than for a student working alone.

Students are informed of the need to think about a topic for their experiment at the beginning of the semester. They have about seven weeks to plan their actual experiments, and are then expected turn in a brief proposal two weeks prior to the date of the actual experiment. The proposal should include the objective to be tested, theoretical background, hypothesis statement, list of materials, and procedure. Specifically, the details of the assignment are presented here:

Biochemical Engineering Laboratory (CHE 194) Inquiry Experiment Assignment

I. Statement of Objective (10 pts): A statement of the objective states the purpose and goal of the experiment as concisely as possible (1-2 sentences). The objective of the inquiry experiment may be related to other experiments done in CHE 194, however it cannot be to simply repeat an experiment that did not work the first time. The objective should identify the dependent variable to be tested, the independent variable, and constants in the experiment.

II. Theoretical background (10 pts): The theoretical background should provide the necessary information to

- 1) justify the significance of the experiment
- 2) explain the principles behind the techniques to be used
- 3) inform the hypothesis regarding the outcome of the experiment. Information from published literature, a mathematical model, or other sources may be used to inform the hypothesis.

III. Statement of Hypothesis (10 pts): A hypothesis is an educated guess about a possible outcome of the experiment. This should be one or two sentences to concisely state the expected outcome of the experiment.

IV. Materials needed (10 pts): A complete list of materials required for the experiment is to be provided, including chemicals, equipment, etc.

V. Procedure (10 pts)

1. Special preparations should be listed and clearly identified, such as steps that cannot be completed during the lab class but need to be prepared ahead of time. If there are no special preparations, state "none."
2. Describe special equipment preparation, such as temperature control, pH control, etc that has not been part of other experiments performed during the lab class. If there are no special preparations, state "none."
3. List the steps of the experiment that will be performed during the laboratory class time. Approximate the length of time that will be required for each step. If some steps can be performed simultaneously, note which ones will be done together.
4. Prepare a table of runs to be performed if there are more than 3 runs. List the concentration of chemicals in each of the samples to be tested.
5. Clearly identify any safety issues that should be addressed for this experiment. Necessary personal protective equipment should be listed, any special equipment considerations, as well as disposal requirements.

VI. Results (20 pts): Results are facts that were determined during the experiment, and not inferences. The result section should describe the outcome of your experiment, accompanying the appropriate tables or graphs. Where possible, straight line plots should be presented as an equation for the line, including the relative variance (R^2) value. Tables and graphs should include all units and error bars where appropriate. Present all average values or values calculated from measurements including the standard error.

VII. Discussion (20 pts): An interpretation of the results section is included here. Inferences that can be made, based on the results, should be presented and justified. Information from published sources may be used to support your interpretations. Based on information from the discussion, conclusions will be formulated. Present the information in a logical order. Finally, the source and magnitude of errors in the experiment should be presented.

VIII. Conclusion (10 pts): Conclusion statements should be clear and concise. The conclusion should have technical content, not a summary of the actions you performed in your experiments. The content of the conclusion should partner the objective statement.

IX. References: List all literature sources used to prepare the experiment and report.

Table 2 contains the rubric that was used for grading the inquiry experiment.

TABLE 2
INQUIRY EXPERIMENT GRADING RUBRIC

Statement of Objective		
1	2	3
Objective is irrelevant or indicates some lack of understanding	The objective is somewhat different from other experiments	The objective is clear and is novel and significant
No mention of parameters to be measured	Adequately stated	Dependent variable and constants are clearly identified
Theoretical Background		
1	2	3
Significance of experiment is not justified	Significance of experiment is partially justified	Significance of experiment is clearly justified
Principles of the techniques are not explained	Principles of the techniques are partially explained	Principles of the techniques are clearly explained
No support for hypothesis is developed	Support for hypothesis is partially presented	Support for hypothesis is clearly presented
Statement of Hypothesis		
1	2	3
Hypothesis is inadequately or inaccurately stated	Hypothesis is adequately stated	Hypothesis is clearly stated and demonstrates ingenuity
Materials Needed		
1	2	3
List is lacking significant components	List is partially complete, containing the major components only	List is complete and accurate
Procedure		

1	2	3
List of special equipment and preparations is missing or inaccurate	List of special equipment and preparations is partially completed	List of special equipment and preparations is complete
List of steps to be performed is inaccurate or missing	List of steps to be performed is partially completed	List of steps to be performed is complete
No mention of safety considerations	Safety considerations are partially described	Safety considerations are complete and thoughtfully described
Results		
1	2	3
Presentation of results demonstrates erroneous features	Presentation of results is lacking some important details, such as units or error calculations	Presentation of results is complete
Discussion		
1	2	3
Results are erroneously interpreted	Interpretation of results is partially presented	Interpretation of results is clear and complete
Explanation of error is missing or inaccurate	Some error analysis is described	Thorough description of error sources and magnitude is presented
Conclusion		
1	2	3
Conclusion statements are inaccurate	List of conclusion statements is incomplete	List of conclusion statements is complete
Statements have not been justified in discussion section	Statements have been partially justified in discussion section	Statements have been thoroughly justified in discussion section

The proposals were approved by the professor and some adjustments to methodology and materials made, before students performed the experiments. In one inquiry-laboratory period, students explored the following objectives either alone or in groups:

1. The effect of temperature on the retention time of green fluorescent protein through a hydrophobic interaction chromatography (HIC) column
2. The effect of pH on the kinetic rate constants of trypsin hydrolysis of benzoyl DL-arginine p-nitroanilide hydrochloride
3. The effect of plasmid DNA on the maximum growth rate of *E. coli*
4. Analysis of a band from an agarose gel containing the GFPuv gene by restriction cut
5. Rate of degradation of GFP by the protease in Tide laundry detergent
6. The use of magnesium nitrate as the concentrated salt in the hydrophobic interaction chromatography purification of green fluorescent protein

The students learned valuable skills from their experiments, particularly from the experiments that did not work as they had hypothesized. In some cases, unexpected obstacles arose that made the experiments very difficult to complete. For example, student number 6 had done a thorough review of how salts are chosen for HIC chromatography. She

found the Hofmeister series as an ordering of anions and cations with respect to their ability to salt out proteins, and thus shown to be the proper ordering for designing a HIC experiment [7]. Based on her literature review, magnesium nitrate should have been a superior salt for the purification of GFP as compared with the cookbook class experiment. However, during her experiment, she discovered that magnesium nitrate did not dissolve adequately in water to serve as the high salt buffer component. In her preparation for the experiment, she had failed to check data on the solubility of magnesium nitrate. Thus, she learned the importance of reviewing simple details that can be found in the literature, such as solubility. Likewise, the protease in Tide failed to result in any measurable decrease in fluorescence of GFP in experiment number 5. The student tried the experiment at several pH values but without any effect. In his effort to try different pH values, he developed his ability to use acids and bases to adjust the pH of buffers without overshooting (it took several tries in each case to get this procedure down). The students in experiment 2 had already completed the enzyme kinetic experiment at a pH of 8 during the “cookbook” lab period. However, for the inquiry, they tried to carry out the experiments at pH 6 and 10. In this experiment, they found that, based on the slope of the rate vs. substrate plot, the Michaelis constant (K_M) increased both at pH 6 and 10. Because the substrate precipitates at concentrations slightly higher than that necessary to measure the kinetic constants at pH 8, the actual kinetic constants were outside the measurable range in their inquiry experiment. From this exercise, the students learned that measuring enzyme kinetic constants is a complex endeavor. As in a “real-life” study, when one does not know the kinetic constants ahead of time, it can be challenging to determine the appropriate concentrations of enzyme and substrate to use for determining these constants. This challenge was not apparent to students after completing the cookbook experiment, where the range of concentrations had been determined for them.

The students experienced frustration when their experiments did not work, however, this experience models the actual research experience of checking the literature for all necessary information, developing an efficiency at preparing solutions with the proper pH and concentration for an experiment, and learning to consider all the factors that can influence an experiment prior to trying it out. It is difficult to learn the various aspects of designing and preparing an experiment through a cookbook lab because the experiment has already been designed to factor out trial and error.

STRUCTURAL MECHANICS LABORATORY

Student learning objectives related to experimental design skills are being enhanced in the Civil Engineering curriculum as an outcome of the PS³ partnership. Changes will involve the Engineering Mechanics Laboratory course (CE113), a one semester, three-hour per week required course for all Civil Engineering and Mechanical Engineering undergraduates at SJSU.

The course traditionally has been taught as a series of cookbook experiments. At present, student teams conduct five experiments throughout the semester on various aspects of structural mechanics. Teams follow a prescribed test procedure, investigate experimental questions designated by the instructor, and write laboratory reports explaining what they have done and their responses to writing prompts defined in the lab assignment.

The first alteration to this form of instruction occurred in Spring 2005 when the workload of student teams was refined. Instead of delivering written reports on all the experiments, teams were assigned to write detailed reports for two experiments and only abbreviated summaries of the procedure and results for other experiments. Each team delivered one of their detailed reports to the class as an oral presentation. This revision of workload allowed students to put more emphasis into a few experiments, with the goal of having students leave the course with deeper understanding of one aspect of mechanics as opposed to a shallow understanding of all topics covered in the course.

The next revision of the course will focus upon design of experiments. Design of experiments has been a stated learning objective of the course for many years, but past assessments of students knowledge about experimental design has provided evidence that students are not working at a level that most employers would expect. Also, when students were asked during a focus group assessment to explain what they had learned about experimental design, responses indicated that students could not differentiate between design of an experiment and experimental testing of a design. In response to these observed weaknesses, the sequence of experiments will be used to require students to take a progressively more active role in the experimental design.

Student involvement in experimental design will occur in three steps and involve all the experiments. The first two levels will use the first four experiments, which will remain in a cookbook format. In these experiments, the instructor will pose the experimental question, assign the test specimen variables, and provide a complete test procedure for the students. In the first experiment (level 1 experimental design), the student manual will explicitly provide all of the information corresponding to each experimental design step, as listed in Table 1. In their reports, students will be required to list the design steps, the corresponding information, and its relevance to the experiment, essentially repeating much of the information in the manual.

The second, third and fourth experiments, comprising the second level, will use the existing student manual, which provides information about the design of the experiment but does not explicitly describe the design factors according to the steps in Table 1. Students will use Table 1 to describe the design process and identify from the student manual the experimental design factors in their final report. These experiments will be conducted by all teams, but each team will be expected to provide a detailed written and oral report for one of the three and abbreviated reports for the other two.

The third level will allow the student team more choice about the design of the fifth experiment, a column buckling experiment. This experiment was chosen because it allows for significant variation of the independent variable, the lengths of the test specimens, using the existing testing facilities. In the past, specimens were cut to lengths at multiples of 75 mm. Each student team tested the same set of five lengths. In addition, the dependent variable of the experiment (the buckling force) was assigned by the instructor. To enhance student experimental design skills, three possible dependent variables will be offered by the instructor, and each team will choose one to investigate. The student team will also identify a series of specimen lengths (the independent variable) to use in their experiments. Specimens will be available in lengths cut to multiples of 25 mm and students will be restricted to testing at most five specimens.

A stepped approach for increasing demands on students for the design of experiments has been chosen as an instructional methodology for multiple reasons. The initial cookbook experiments allow the students to become familiar with experimental design, and laboratory procedures and equipment. Critical evaluation by the students of the second of the three levels requires students to process their learning. The third level requires students to implement this skill in designing an experiment that answers a question that they have chosen.

Several factors went into the choice of which experiment to alter to allow for student experimental design. First was identifying the experiment that could easily accept a wide variety of specimens using the existing testing fixtures and equipment. Second was choosing a content subject that could be adapted to use student's prerequisite knowledge (CE 112 as described earlier in this paper). In the prerequisite theory course, students are introduced to two of the failure modes in the experiment. The third failure mode is taught in the laboratory course, but introducing theory during the laboratory has been complicated, particularly for students who have struggled with the prerequisite course. This new format will deemphasize the third mode of failure, and if possible, exceptional students may be challenged to investigate this mode on their own, in a form of differentiated instruction. A third factor was defining an appropriate level of workload for the students and faculty. Emphasizing experimental design skills will take time and will require the instructor to reduce the theoretical content that is currently taught in the laboratory course. The fourth factor in selecting this experiment is the need for additional test data. Since experimental results vary from theory for multiple reasons, the course instructors identified a need to provide students with additional data to supplement their own experiments. An online database of prior experimental results will be available for students, to strengthen their skills at reviewing the work of others and evaluating its' suitability to assist them in 'augmenting' the data used to test their own hypothesis.

One goal for the modifications is that students will leave the course with a better understanding of the design of experiments. Another goal is that students will gain a deeper

understanding of two of the topics investigated by the experiments, rather than a superficial understanding of five topics. Their deeper understanding will result from the one cookbook experiment for which the students provide a written and oral report, and the experimental design experiment where the students are involved with the design. Benefits are also expected in the skills required for communication and life-long learning. The course is still expected to contain a total of five or six experiments, but the modification of information provided for the students should improve their experimental design skills. Assessment of student learning will be conducted through evaluation of their reports using a rubric intended for experimental design and by written questions as part of the course final exam. The timeline for implementing the complete changeover to the new series of lab assignments is Spring 2007.

CONCLUSIONS

The original five-year grant has two remaining years. As such, the enhancement of the engineering education derived from this project is ongoing. At this point in time, the conclusions are:

1. Participation of engineering faculty in workshops for K-12 science teachers has led to enhanced teaching in several lecture and laboratory courses in at least three engineering programs at SJSU.
2. Several laboratory courses have been revised to allow students to take a larger role in designing experiments. Additional laboratory courses are currently being revised to incorporate open-ended experiments.
3. Several lecture courses have been revised to include inquiry based learning as an instructional pedagogy.
4. The improvements in (2) and (3) have been critical in meeting several outcomes of Criterion 3 in the new ABET Engineering Criteria 2000, such as 3b (design of experiments), 3e (ability to identify, formulate and solve engineering problems), and 3i (lifelong learning skills).

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