Developing inquiry-based laboratory exercises for a mechanical engineering curriculum

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**Disciplines**
Engineering Education | Mechanical Engineering

**Comments**
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AC 2012-5155: DEVELOPING INQUIRY-BASED LABORATORY EXERCISES FOR A MECHANICAL ENGINEERING CURRICULUM

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Terrence R. Meyer obtained his bachelor’s in mechanical engineering from the University of Minnesota Minneapolis, St. Paul, in 1993. He then worked as a design engineer for Cummins Engine Company until returning to academia as a National Science Foundation Graduate Fellow at the University of Illinois, Urbana-Champaign, in 1994. After completing his Ph.D. in the area of laser diagnostics and turbulence in 2000, he joined a research group conducting combustion and laser-based diagnostics for the Air Force Research Laboratory until joining the faculty at Iowa State University’s Mechanical Engineering Department in 2006. He is currently the William and Virginia Binger Assistant Professor in mechanical engineering and is the Coordinator for the department’s Clean Energy Technologies program.
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Abstract
This paper describes the development of two inquiry-based experiments in a mechanical engineering curriculum at a land grant research-intensive university, aimed at providing students with the opportunity to design and perform experiments. One experiment in engineering measurements (system behavior) and one experiment in fluid dynamics were developed. In each case, students working on teams were posed with a scenario and question to answer. For example, in the system dynamics experiment, students were asked to verify that a thermal system and electrical system were mechanically equivalent systems. In the fluid dynamics experiment, students were asked to investigate drag coefficients for flow over a sphere over a range of Reynolds numbers. The students were required to formulate the theoretical approach and solve based on given information and assumptions. Subsequently the students were required to plan an experiment using available equipment to obtain data to support their theoretical approach. Once the experimental plan was reviewed to avoid critical errors, students completed the experiment and compared solutions to theoretical predictions. Students write a paper on the laboratory exercise, which is graded against a defined rubric that assesses the work on various areas including theoretical approach, experimental approach, data reporting and discussion of results. The overall feedback from students (through online surveys) and lab instructors (through discussion) was generally positive. In particular students found the open-ended approach difficult and challenging compared to other prescribed laboratory exercises but more beneficial to understanding the topic of interest. Opportunities for improvement include better articulation of the laboratory objectives and discussion of the philosophy and intent of the laboratory a priori in order to inform students of the different expectations of inquiry-based activities.

Introduction
The most common pedagogical approach to engineering and science is the traditional one of deductive teaching. The instructor introduces a topic by focusing initially on general principles and model development, followed by illustrative applications, finally giving students practice in solving problems along similar lines. The aspect of ‘how’ is given importance while the question of ‘why’ is undermined or neglected. What practical problems can they be used to solve, and why should the students care about any of it? Leading educational theorists agree that this approach is not always successful in fostering understanding, synthesis, eventual application of knowledge, and the ability to use information. A well-established precept of educational psychology is that people are most strongly motivated to learn things they clearly perceive a need to know. A preferable alternative is inductive teaching and learning. Instead of beginning with general principles and eventually getting to applications, the instruction begins with specifics—a set of observations or experimental data to interpret, a case study to analyze, or a complex practical problem to solve. This approach provides students with an opportunity to develop creative ideas, find alternative sources of information, ask open-ended questions, predict and test ideas before acceptance, challenge the ideas of others, collect evidence to support ideas,
and restructure concepts based on new evidence is suggested. Inductive teaching and learning is an umbrella term that encompasses a range of instructional methods, including inquiry learning, problem-based learning, project-based learning, case studies-based teaching and just-in-time teaching.

**Inquiry based learning**

Inquiry is the simplest of the inductive approaches and might be the best one for inexperienced or previously traditional instructors to begin with. It requires designing instruction or activities so that as much learning as possible takes place in the context of answering questions and solving problems. As the students gain more experience with this approach, the instructor may increase the scope and by assigning more open-ended and ill-structured problems and simultaneously decrease the amount of explicit guidance provided. Inquiry learning may be considered an umbrella category that encompasses several other inductive teaching methods. Studies have indicated there are variations of inquiry based teaching methods such as 1) *structured inquiry* (students are given a problem and an outline for how to solve it); 2) *guided inquiry* (students must also figure out the solution method) and; 3) *process-oriented-guided-inquiry-learning* (POGIL) in which students work in small groups in a class or laboratory on instructional modules that present them with information or data, followed by leading questions designed to guide them toward formulation of their own conclusions. The instructor serves as facilitator, working with student groups if they need help and addressing class-wide problems when necessary. Inquiry-based methods have been used extensively in the sciences and to a lesser extent in engineering.

**Rationale for described work**

This paper describes the development of two inquiry-based experiments in a mechanical engineering curriculum aimed at providing students with the opportunity to design and perform experiments. The design and profile of the new experiments best fit the POGIL profile in our opinion and are the first of its kind in our curriculum. The motivation behind the development of the laboratories was to incorporate learner-centered based approaches in the laboratory aspects of the curriculum, which historically has been focused on analyzing and interpreting data. The two laboratory exercises were implemented in two junior-level core classes - one experiment related to system dynamics (mechanical system) in an engineering measurements class and one experiment related to fluid dynamics (thermo-fluid system) that was implemented in a fluids class. Both classes are 3 credit (semester) classes that involve a laboratory component. Common features of the two courses include 1) a common large lecture format with smaller laboratory sections; 2) students working in groups of 2-3 in the laboratory and; 3) graduate students serving as instructors for the laboratory sections. The typical enrollment for each class is 120-130 students each semester. Results from direct and indirect assessment of the student performance in the laboratory are also presented along with the future outlook for these laboratories and instructional methods within our specific curriculum.

**Approach to designing experiments**

The approach to developing and implementing a POGIL-based exercise involved moving away from the more structured ‘canned’ instructional lab where students are typically told stepwise what to do in order to collect certain data. Such a format usually ends with a requirement analyze the data, such as determining uncertainty levels, their fit to existing models etc. Rather,
in each case, students working on teams were posed with a scenario and question or questions to answer. The students were required to formulate a theoretical approach and arrive at a theoretical solution based on given information and assumptions. The students were expected to utilize the knowledge gained previously in the lecture and laboratory elements of the course, as well as in reading material available from the literature. Subsequently the students were required to plan an experiment using available equipment or by purchasing equipment using a fixed budget to obtain data to support their theoretical approach. Once the experimental plan was reviewed to avoid critical errors, students completed the experiment and compared solutions to theoretical predictions. It was emphasized that students needed to discuss and explain observed differences between experimental and predicted values, thereby allowing them to examine the validity of theoretical constructs and assumptions as well as uncertainties in the measurement process. Students were finally required to write a paper on the laboratory exercise, which is graded against a defined rubric that assesses the work on various areas including theoretical approach, experimental approach, data reporting and discussion of results. Throughout the exercise, the laboratory instructor serves as a passive guide and mentor. Although the students were allowed to ask questions for clarification, the laboratory instructor did not divulge particular methods that the students might employ. Since all our lab instructors were graduate teaching assistants, it was important to ensure that all of them had run through the entire lab a priori so that they could be in the best position to guide the students. In this context, a trial run and a frequently asked questions/typically encountered problems sheet proved useful in getting them ready for the labs. The salient features of each inquiry-based experiment are described next.

**Engineering Measurements laboratory exercise: Investigation of first order systems**

One of the key topics covered in a junior level Engineering Measurements class is that of system behavior (dynamics) with a focus on first and second order systems. The related course outcome is to ‘recognize a measurement system's dynamic limitations by understanding first-order and second-order behavior, and to characterize frequency response.’ One of the laboratory exercises pertains to first order systems, which was replaced with the newly developed inquiry-based activity described below.

The student teams were given two physical systems as shown in Figure 1 - an electrical system (RC circuit) whose quantity of interest is the output voltage and a thermal system (box with a thermistor serving as a heat source) whose quantity of interest is the air temperature inside the box. All necessary specifications for each system (e.g. R, C values and dimensions, thermistor and resistance thermometer specs) were provided. An appendix that serves as a refresher of topics covered related to first order systems and the physical systems was also provided (e.g. key points for first order systems, basic circuit theory and basic heat transfer equations). Finally they were given a list of the laboratory equipment available for them to use. These included resistance thermometers, signal generators, voltmeters, oscilloscopes, connectors etc. The objective of the laboratory was for the students to test the claim that the two physical systems were equivalent systems and to justify their answer using experimental data.
The expectation was that students would synthesize previously covered lecture content to discern what they would have to do to test the claim. In this case they need to recognize that equivalent systems are those that have the same form (order) of the governing equation for the quantity of interest and comparable (same order of magnitude) values of the dynamic quantity of interest (time constant, $\tau$, for a first order system). The requirement that they justify their claim using experimental data would require them to then design a set of measurements to establish the behavior of the system and determine the time constant. The students would have to recognize that the time constant could be obtained from a plot of the output quantity (voltage in the electrical system, temperature in the thermal system) as a function of time. In this regard, students would have to establish the frequency of measurement and how long they should measure based on theoretical considerations. As one can see, this is drastically different from a typical instructions-based laboratory. To establish expectations, they were given a list of deliverables (in order): 1) a completed planning document that would establish theoretical framework for analysis, including assumptions and that would ‘map’ out their planned experimental procedure; 2) a formal technical report detailing their methods, results and conclusions. The technical report was expected to include theoretical framework, estimated system parameters, a sufficiently detailed experimental procedure, results (plots, comparison of experimental and theoretical values), discussion of observed differences and conclusions regarding the claim (objective).

The planning document forms an important part of this exercise and serves two purposes. First, it guides the student’s approach to establishing the governing equations of the systems and subsequent experimental plan. For example it specifically asks students to list assumptions made and establish the theoretical estimate of the governing dynamic quantity. By applying the relevant principles (circuit theory, energy balance), students should arrive at a first order equation describing the quantities of interest (output voltage of RC circuit and air temperature for thermal system). From these equations, they can establish theoretical estimates for the time constant – RC for the circuit, where $R$ is the resistance and $C$ is the capacitance; and $\rho Vc_p R$ for the thermal system, where $\rho$, $V$ and $c_p$ are the density, volume and specific heat of the air respectively and $R$ is the effective thermal resistance. The document then asks the students to establish their experimental procedure with sufficient detail (e.g. what equipment they will use, what signals they will measure, what excitation signals (if any) they will use, what quantities are
they planning to measure (plots), how do they expect the data to look like etc.). As an example, students would have to recognize the need to provide a step input to the circuit in order to measure the time response and extract the time constant for each system (e.g. constant input DC voltage to circuit and thermistor). The second purpose of the document is that it encourages the students to think about factors that may cause their experimental results to deviate from theory. For example, assumptions made to include or disregard conduction effects of air in the thermal box may affect the theoretical estimate of the thermal resistance and time constant or improper insulation may affect the steady state response. Students must have this planning document checked off or approved by the instructor prior to proceeding with any experiments. The rationale for this ‘checkpoint’ is to ensure that 1) the theoretical framework is not way off base (e.g. equation does not represent a first order system) and; 2) the planned experiments do not have critical errors that may inadvertently cause damage to any laboratory component (e.g. short circuits, input voltages beyond device ratings etc.). Once approved, the students then proceed with the experiments, gather the data and complete their report.

Most of the students had difficulty in establishing the theoretical framework for the thermal system and in most cases did not account for all modes of heat transfer (convection and conduction of air) or missed the fact that convection and conduction occur in parallel in their calculation of R. As expected several students had difficulty in setting up their own experiment.

**Fluids laboratory exercise: Determination of a drag coefficient**

A similar inquiry-based exercise was developed for the junior level Fluids class, addressing the topic of drag coefficient.

In this laboratory, students were informed that their objective was to experimentally investigate the drag coefficient ($C_D$) for flow over a spherical object of diameter $D$ in the Reynolds number range from $Re_D = 0.01$ to 10,000. Their deliverables were (1) a plot of $C_D$ vs. Reynolds number ($Re_D$) and a correlation (fit) of the form $C_D = C_1 \cdot Re_D^{C_2}$, specifying constants $C_1$ and $C_2$ for the regime where $Re_D \leq 1$; (2) a plot of $C_D$ vs. $Re_D$, for $Re_D > 1$ with the typical range of $Re_D$ from $\sim 10$ to 10,000; and (3) at least one picture of the experimental setup. They were also asked to include error bars by collecting multiple measurements per data point and to report the uncertainty ($R^2$) of their correlation. The drag coefficient was defined as $C_D = F_D / (0.5 \rho U^2 A)$ where $F_D$ is the drag force, $\rho$ is the density of the fluid, $U$ is the average velocity of the incoming flow, and $A = \rho D^2/4$ is the projected area of the spherical object. While not specified, the students should have been aware that $Re_D = \rho UD/\mu$, where $\mu$ is the dynamic viscosity of the fluid flowing over the sphere. They were furthermore instructed that they would not be given access to the laboratory wind tunnel an instead would have to rely on the terminal velocity of a falling object to extract $C_D$. They were furthermore instructed that they would have to decide on the physical parameters that would allow the object to attain the $Re_D$ regimes of interest stated above. These physical parameters were not defined for the students, but would consist of the diameter $D$ and choice of fluid for the experiment. Each group was then given a small budget of $15 to purchase materials for the experiment. They were expected to build an experiment and provide the deliverables above within this budget.

In order to complete the experiment, the students had to realize that plotting $C_D$ vs. $Re_D$ required them to design an experiment in which they would have to drop sphere into a fluid and measure
its velocity after it reached its terminal (constant) velocity. They would also need to know the weight of the sphere as the drag force, $F_D$, would balance out the weight when it reached its terminal velocity. However, reaching the range of $Re_D$ from 0.01 to 10,000 required students to vary $\rho$, $U$, $D$, $\mu$, or a combination of these variables. Hence, they could potentially purchase a number of balls with varying diameter, but they would quickly find that they would deplete their funds before reaching the full range. However, they could cut the cost significantly by also varying $\rho$ and $\mu$ by changing the type of fluid. Hence, use of both air and water, which are both relatively inexpensive, would help students reduce their costs by a factor of two. In the first offering of this experiment, one group was creative and realized that they could vary the velocity $U$ while keeping the diameter constant by filling the sphere with varying amounts of sand. Hence, students by necessity had to utilize their knowledge of fluid mechanics to conduct the experiment within the given budget. Figure 2 shows the equipment and weighted spheres used by one group for their experiment. After determining their material dimensions and operating ranges, the students could conduct their experiments and compare their $C_D$ vs. $Re_D$ vs. measured values already available in the textbook. If their experiments did not match the expected values, they may have had to consider other effects, such as buoyancy (in the case of drop tests in a water tank) or surface roughness that may have affected their data. Many students successfully conducted experiments but failed to consider these other sources of uncertainty. Also, many students were able to attain part of the $Re_D$ range, but few were able to reach the full range from 0.01 to 10,000.

![Fig. 2: Components used for fluids activity. (a) weight balance; (b) plastic tank with water and (c) spheres with different diameter and weights, along with stopwatch.](image)

**Assessment of student performance**

The laboratory reports were graded against a rubric that was made available *a priori* to the students to clarify expectations and grading schema. The rubric lists the various expectations and specific items to be included in the report. An example of the rubric used in the engineering measurements class is shown in Figure 3.

**Assessment of lab exercises**

The engineering measurements laboratory was piloted in Spring 2011 while the fluids laboratory was piloted in Fall 2011. Feedback was sought from both the lab instructors’ perspective, through face-to-face meetings and from the students’ perspective through online surveys. Both were conducted approximately one week after completion of the lab exercise. Some common observations included the following:
Students initially seemed to have difficulty understanding the objective of the projects and spent an inordinate amount of time questioning the lab instructors on how to get started.

Lab instructors felt that several student groups overly relied on pointers from the instructor or other groups rather than proceeding on their own.

Lab instructors felt that more often than not, developing the theoretical framework took students longer than planning/executing the experiment.

Student feedback was obtained through a short anonymous online survey. The response rate was approximately 65% for the two classes. A brief summary of the more important points relating to the lab experience is provided below.

- 63% responded that the laboratory exercise was sufficiently challenging and a good learning experience. 35% responded that it was too difficult and not a good learning experience. About 3% responded that it was too easy to be a useful learning experience.
- 85% of the students indicated that having a planning document as an intermediate checkpoint was useful.
- 71% of the student responses agreed that such as inquiry-based approach was a better learning experience than a typical ‘follow the steps’ laboratory.

The comments gave some more insight into the challenges faced by the students and opportunities for improvement. As might be expected, students found the exercise to be very different from their previous experiences because it was completely open ended. They, in fact, had to conduct the experiments on their own time and devise their own measurement approaches without supervision from a graduate teaching assistant. Some complained that the exercise took more time than the other laboratories and that it should count for more points, and some complained that the instructions were not very clear as noted in this sample comment: ‘Great lab and idea but a little bit of direction would of helped to get things started.’ These points echo the observations of the course instructors. Clearly there are opportunities for improvement in terms of articulation of the objectives and some discussion of the philosophy and intent of the laboratory during lecture.

It was rewarding however, to note that the overall feedback was quite positive. One student noted that, ‘The lab experiment was very useful. This was the first design lab that I did where I understood what and why we had to do. I learnt a lot about planning and designing of experiments to get a specific value to answer or a range of answers. Was a good experience.’ Some students did indeed see the clear benefit in this learner-centered approach as evidenced by the following comment: ‘The difference between the open-ended lab and the "follow the instructions" type lab was that I learned so much in preparing for the open-ended laboratory....For the open-ended lab I had to do research and work out calculations which really helped me to understand the concepts in the lab. I am not suggesting you do this for every lab because I put about 10 hours of work into the planning document, but possibly adding one more lab like this?’
Summary and outlook
This paper describes the development of two inquiry-based experiments for a mechanical engineering curriculum aimed at providing students with the opportunity to design and perform experiments. These labs were designed to foster learner-centered activities and were among the first ‘open-ended’ laboratories to be implemented in our curriculum. In particular, it gave students the ability to design, conduct, assemble, and troubleshoot an experiment that was not provided for them. The experiment, if designed poorly, was not guaranteed to succeed. To succeed, students had to utilize the concepts they learned in class to optimize the experiment, which encouraged interest in learning those concepts. The overall feedback from students (through online surveys) and lab instructors (through discussion) was quite positive. In particular students found the open-ended approach difficult and challenging compared to other prescribed laboratory exercises but more beneficial to understanding the topic of interest. Opportunities for improvement include better articulation of the laboratory objectives and discussion of the philosophy and intent of the laboratory during lecture. The latter is to help
address the fact that student expectations from other courses do not line up with inquiry-based activities. We note that in our view, this format of inquiry-based exercises can be implemented in stand-alone laboratories as well as integrated lecture-lab courses such as the ones described in this work. We plan to continue fine-tuning the laboratories to enhance the learning experience. Informal feedback from the department’s industrial advisory council during the Fall 2011 meeting suggests that this format should be the dominant one for all the laboratory experiences. It is anticipated that this inquiry-based approach will be adapted to other laboratory courses.

References


