Designing a Laboratory Ecosystem Framework, and Scaffolding an Interactive Internal Combustion Engine

Dr. David MacNair, Georgia Institute of Technology

Dr. MacNair serves as Director of Laboratory Development in the Woodruff School, and manages Junior and Senior level laboratories in Mechanical Engineering. He develops innovative laboratory experiences based on lessons-learned from the maker movement and real-world industrial challenges, and is building an "ecosystem" of academic laboratory equipment and curriculum resources which allows universities to collaborate on the development and execution of effective undergraduate laboratory experiences.

Dr. MacNair joined the Woodruff School in 2015 after working for the Georgia Tech Research Institute, and as an Educational Consultant for Enable Training and Consulting and National Instruments before that. He received his BS in Mechanical Engineering in 2008 and his PhD in Robotics in 2013, both from Georgia Tech.

In his non-work hours, David serves as founder and President of the Atlanta Maker Alliance (Atlanta Leadership for the Maker Movement) as well as Executive Director of the Roswell Firelabs (a community education-focused maker space). He also guides the development and investment of various Atlanta-based foundations and non-profits targeting K-12 education.

Mr. David Edward Torello, Georgia Institute of Technology

Dr. David Torello graduated with his B.S. in mechanical engineering from UC Berkeley and his M.S. and Ph.D. from the Georgia Institute of Technology. He is currently non-tenure track faculty in mechanical engineering at Georgia Tech, lecturing in mechanics related disciplines and directing the A. James Clark Scholars Program.

Dr. Jeffrey A. Donnell, Georgia Institute of Technology

Jeffrey Donnell coordinates the Frank K. Webb Program in Professional Communication at Georgia Tech's George W. Woodruff School of Mechanical Engineering

Designing a Laboratory Sequence and Scaffolding an Interactive Internal Combustion Engine Lab Project

Introduction

Laboratory courses are an important part of undergraduate engineering programs. They are specified in ABET's list of student outcomes, they provide concrete experiences to reinforce lessons taught in lecture classes, and they give students some of the relatively few hands-on experiences available in traditional engineering programs. However, while specific problems have been difficult to identify, laboratory courses have for many years been a source of discomfort and concern among engineering faculty. In 1983, Ernst outlined problems of focus and staffing that we still confront today [1]; Edward's survey makes it clear that these concerns had not gone away by 2002 [2], as does Litzinger's survey of professionals' definitions of expertise [3]. The training of the graduate teaching assistants who commonly staff labs is a concern for laboratory courses from [4, 5], and Nikolic's approach to resolving problems in a laboratory course indicates that for many programs the design of the laboratory course—even if flawed—may be so hard to change that programs consider investing in staff members simply to solve problems [6]. Alternatively, numerous recent publications have made it clear that e-learning—both as remote labs and as virtual labs—is under consideration to solve the numerous problems raised by laboratory courses in the engineering and natural sciences. [7-11]

To understand laboratory courses, it is helpful to examine the way that goals are established and addressed. Feisel and Rosa [12] identify a fundamental problem in that there appears to be no overall agreement on the goals of engineering lab courses (p. 6), and they note that stated objectives do not clearly translate into actions that can be taken and assessed in a class. Their discussion also points out that the introduction of increasingly powerful computers and increasingly complex lab equipment has introduced distractions, with the risk that project instructions and student attention may come to be dominated by the instrumentation rather than by the system under study. Ernst's classic article [1] speaks to a similar concern with project goals, pointing out that many instructional lab projects are designed as demonstrations in support of lecture topics rather than as data-collecting investigations. By this analysis, some lab classes may seem to be deceptively titled, or to have wandered from their missions. In another type of strategic study, Litzinger [3] explores the question of what a lab course ought to be like, and finds that most undergraduate lab classes offer poor models of learning environments. In his analysis, labs can be distilled into those focusing on component, or mechanical, skills—involving mastering the use of instruments or analysis methods—or into those that seek to foster the cognitive skills that we characterize as thinking. The takeaway from this analysis is that labs need to be conceived in a way that cultivates particular thinking processes and that the lab experience by which the student will realize that thinking process needs to be orchestrated in advance.

These analyses suggest that the problem with labs is not simply one of size and equipment; it goes to the way we as instructors establish learning goals for our students and how we design their lab experiences in support of those experiences. At Georgia Tech's Woodruff School of

Mechanical Engineering, we have taken such analyses to heart in our redesign of an existing sequence of laboratory courses. We have abandoned procedure-focused lab instructions in favor of an inquiry-based method that emphasizes thinking and that facilitates the students' making connections between concepts. To reduce the distractions offered by complex instruments, we have introduced a simplified data collection ecosystem, we have redesigned our lab manuals to reduce the number of tasks the students must complete, and we have adjusted our grading rubrics to emphasize demonstrations of system comprehension.

In the next sections, we will give an overview of our general approach, with reference to learning studies that are particular to the engineering domain. Then we will present two projects, conducted in our required third-year and fourth-year laboratory classes, to indicate both how we cultivate student learning and how our method can be used as a stable environment to promote learning as students progress through the curriculum, from analyses of simple devices to studies of more complex systems.

Background

The development of an inquiry-based lab class was reported in 2017 [13]. Using this background, we recognized the need for a clear and coherent course, so we defined the **mission** (or theme) of our course as **problem solving**; we view problem solving as an agentive, or active and thinking-intensive process [14], and we contrast this with the more typical approach to lab classes as a smorgasbord of demonstrations drawn from various research concentration areas [1]. The significance of agentive learning is its focus on information mapping—the act whereby a learner relates—maps—a newly learned skill or concept to a previously held skill or concept. Students learn by creating cognitive information maps. This mapping activity requires time and effort from the student, and instructors can usefully intervene to facilitate this process to the extent that they know what students are being asked to learn and when they are being asked to do this. Our insight is that in a laboratory class, we can easily promote critical mapping by reviewing students' data and results as they are obtained. We do this by preparing lab manuals that promote the students' inquiry processes, that call for presentation of only a few critical, concept-related results, and that are graded on the comprehension the student presents rather than on the numerical accuracy of the results.

In support of this mission, we designed our undergraduate lab class in such a way that the students' attention would be concentrated on content material that we most valued—how to develop experiments that solve problems and how to understand and explain that work. Following Litzinger [15] and Van Meter [16], we identified three problem-solving actions for students to learn in order to successfully and professionally solve problems through experimentation:

1. Identifying and calibrating instrumentation to collect data that will answer the experimental question,
2. Processing and displaying that data in a form that is appropriate to the experimental question,
3. Validating the data by quantifying uncertainty, and by explaining uncertainty in terms of the instrumentation and the system under study.

Implementing these concepts in an inquiry-based project that runs in real time is a challenge. We have constrained our systems so that these are feasible. Thus, as a first step toward a problem solving action we designed and produced an electronics ecosystem simplifies the conceptual problems of wiring an experimental setup by developing simple, single-function electronic components. A representative array of our newly developed electronic components is shown in Figure 1. To avoid the confusing user interfaces of multi-function instruments, our electronic components were developed to be single-function appliances whose functions are labeled on the boards, and are also visible in the circuit layouts. By using these simple tools, we avoid the interface distractions of complex multifunction instruments and constrain our students instead to think directly about the signal flow through an instrumentation setup. This simple electronics ecosystem also reduces the difficulty of debugging errors, allowing students to make productive mistakes while still completing their lab work.

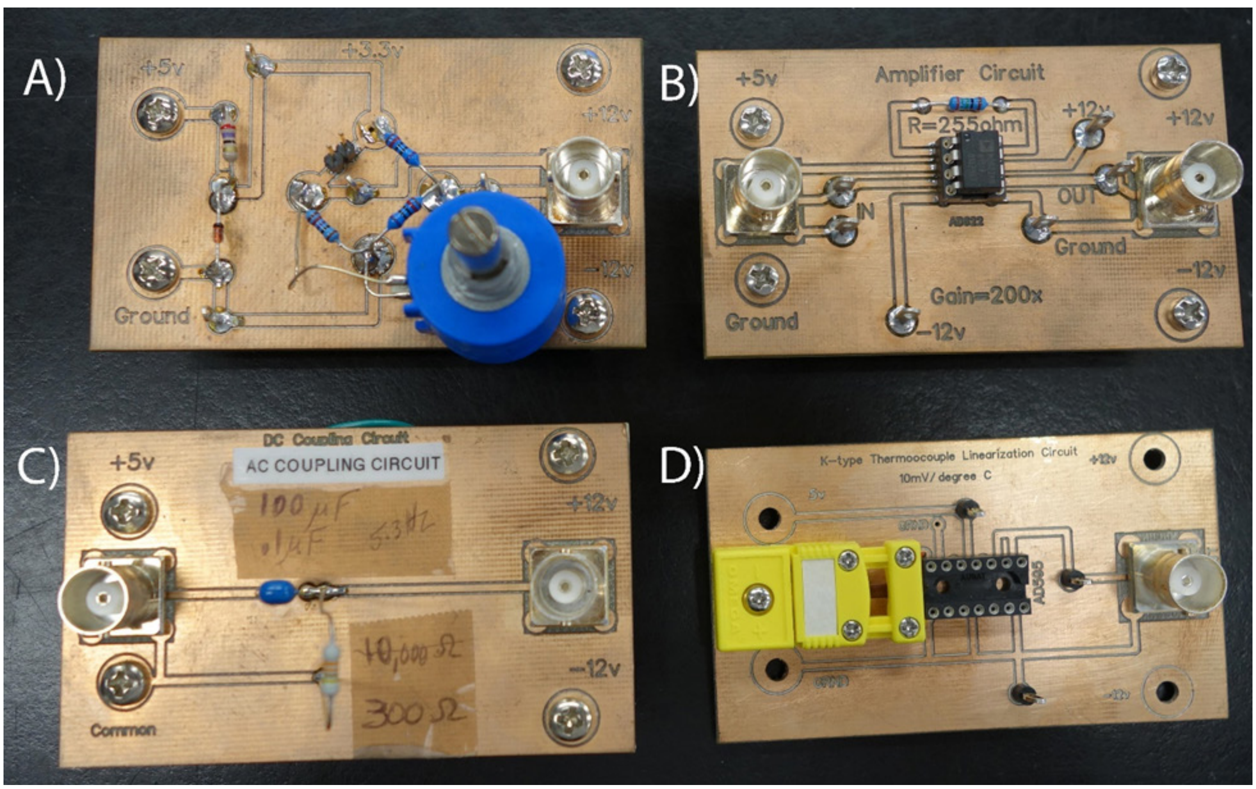

Figure 1. Representative elements of our Electronic Ecosystem. A) Wheatstone Bridge, B) Amplifier Circuit, C) Coupling Circuit, D) Thermocouple Linearization Circuit

For our second problem-solving action, the collection and processing of data, we have avoided the common approach of having students analyze their data after they have left lab. Instead, we want students to do their data processing while they are in lab with their instructors and Teaching Assistants, and we explicitly ask them to display and explain their output displays before they leave. This is a time-consuming activity; to create time to do this, we have reduced the number of required tasks in each lab, allowing us and the students to concentrate on a few, critical concepts. In this way, we are able to verify assure that students understand what they have done and they can correct errors before they leave lab.

Our third problem-solving activity for the students involves the validation of their results by quantifying uncertainty and identifying discrepancies between predictions and measured results. While it is not unusual for lab instructors to require that uncertainty be quantified, we ask students to take the extra step of discussing uncertainty in depth in their project reports, and we calibrate our grading to emphasize these discussions. We feel that discussions of uncertainty and error sources can and should display students' understanding of the system under study and of the instrumentation that they have used to study it. In discussions of uncertainty, we are asking students to reveal their overall understanding of experimentation and of the particular mechanical system that they have explored.

We designed our lab projects to emphasize these problem-solving actions because they are concrete activities that are appropriate to any experimental project. However, these also must all be presented in laboratory reports; we must grade these, and we have been careful to align our grading criteria with our course's mission. We choose—we are able to choose—to value the students' stated understanding of the systems under study above accurate results that may be reported with no explanation to represent the student's understanding of the system in question.

These decisions were deliberate. Our approach correlates with Bloom's Taxonomy of learning [17, 18], as represented in Figure 2.

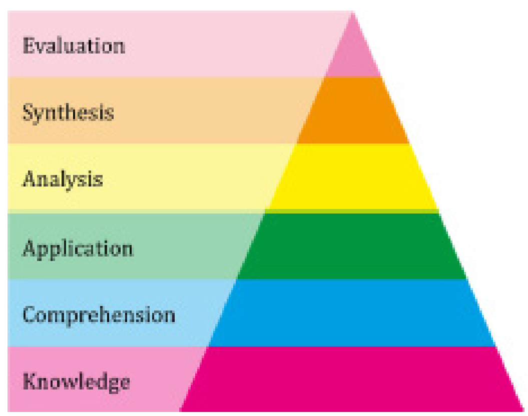

Figure 2. The Bloom Taxonomy Pyramid [19]

By this approach, our objective was to focus our course on the upper levels of the Bloom diagram, emphasizing the students' Synthesis of data and Evaluation of results over their mastery of procedural skills, represented by the middle levels of Application and Analysis. To align our projects with the problem-solving mission of the class, it was important for us to emphasize that the procedural component of a measurement project serves the user's thinking process, but is not the learning goal of the project. This approach was developed intuitively, but we found that it aligns nicely with the refinements offered by recent research on teaching and learning in the sciences.

All lab instructors are aware of the impact Graduate Teaching Assistants can have on students' motivation and learning, and Velasco's argument for training the teaching staff to engage with students reinforces our approach to the important role TAs play [4] in student learning. Specifically, lab staff, usually TAs, is best positioned to interact with students at critical project points, where the student must assess an information representation—data, tabular information or a plot—with respect to the concrete set of instruments and test specimens that it represents. The relationship between data and a system is not always obvious to novices, and it is our job in the labs to insure that students do make such crucial connections. We do this by intervening during lab and asking students to explain their output, after the conclusions of Aurigemma [20]. Van Meter [16] and Litzinger et al. [15] demonstrated, in classroom domains, that students learn best when they are prompted to explain how they relate information in different domains (or how they translate across media). Their examples involve transforming word problems into diagrams and equations, but the principles hold in labs, as investigative goals must be translated into an arrangement of instruments, data must be collected and manipulated, and the relationship of that data to the overall goal must be explained. The critical importance of having students speak to the processes of mode transfer is explored in greater detail in Schunk [21], Mayer [22], Fiorella & Mayer [23], and Jairam & Kiewra [24].

Using these findings, our staff training and our approach to report grading both emphasize students' explanations of their critical steps of information transformation in obtaining and presenting experimental results.

Our Curricular Innovation and Implementation

In the following, we present an overview of our lab curriculum, with a general overview of the two-course sequence, followed by a description of an integrative, multi-week project that concludes the second course of the courses. The mission of the first class, Experimental Methods is to introduce our students to a set of basic and widely used sensors and to teach them to obtain and analyze experimental data by building simple lab setup, calibrating the instruments, taking and analyzing data, assessing error, and finally explaining it all in written reports. The second course emphasizes these previously learned skills while asking students to study complex systems that may require several sensors and data streams. These courses offer a unique approach to laboratory instruction by focusing the courses on the students' understanding of experimentation and by designing the projects as a two-term scaffolded sequence.

Experimentation and Curriculum

The core mechanical engineering (ME) instructional laboratories are Experimental Methods (ME 3057) and Systems Laboratory (ME 4056). Each course aggregated a number of independent and unrelated 1-week laboratory experiences; as a sequence they did not clearly serve an educational goal. As instructors rotated through teaching the lab course, they would redesign a single laboratory experience that was related to their research area, and they would then implement that lab within the single semester they taught the course. The first challenge of redesigning the two-course progression was to refocus the courses on their original intent. Experimental Methods, a 3rd-year course was designed to be a lower-level introduction to sensors and to thinking critically about what those sensors could tell an observer about the real world. The 4th-year course, Systems Laboratory, was then reconceived to introduce students to more complex systems and to ask students to use the sensors from Experimental Methods to perform systems-level analyses. This approach to the course sequence provides both breadth and depth for the students, initially exploring a wide range of sensors across ME domains, and then exploring the way those sensors can be used in a scaffolded approach to systems of increasing complexity.

To provide opportunities for students to think deeply about the concepts we value, Experimental Methodology was reorganized into 2-week long "block" laboratory experiences with the first week introducing new apparatus and a new domain and the second week asking students to answer a core experimental question in that domain. Systems Laboratory, which is still under development, presents more challenging system-level analyses. The course is currently split into two distinct halves, but is evolving toward in-depth blocks of 3 to 6-weeks duration, presenting systems that represent all core areas of mechanical engineering.

The Systems Laboratory block that is most fully developed focuses on the Internal Combustion Engine. Here students perform a complex work/energy analysis on a single-cylinder engine to experimentally derive properties of the system. Sensors on the engine include a force transducer configured to measure torque, a proximity sensor configured to detect student-indicated angles, and a proximity sensor coupled with a toothed wheel to detect wheel angle and angular velocity. From these measurements, students can determine piston and fly-wheel inertial effects, air pressure effects due to piston motion, and energy transfer to and from the back-drivable motor/generator. On the input side, students can connect a pneumatic line to the piston and control the pneumatic valve opening/closing timing to drive the engine. This mimics the motion and control of an engine powered by fuel without risking explosions when students get timing settings wrong. In the future, with the blessing of the Office of Environmental Health and Safety, students will also be able to use the system models they have constructed to control fuel injection and spark plug timing, and then drive the engine with propane fuel.

The Experimental Methods course scaffolds students' understanding to prepare them for the systems-level analysis required for lab projects like the Internal Combustion Engine. The course begins with a simple project in which students characterize of an amplifier to determine its input/output characteristics and limitations (eg. clipping) in order to characterize an unknown system. This exploration touches on the DC response of the system to an input voltage and the frequency response of the system (Bode Analysis), both of which are foundational experimental tests. The experience also provides a connection to and review of their electrical engineering circuits course material, including how to use function generators, oscilloscopes, and how to understand the properties of signals.

In the first two-week project of the course, students explore the calibration of force transducers and displacement sensors used within a Mass-Spring-Damper system. The sensors are treated as an input-output system to tie the work in this project to the lessons learned in the previous project, and students are challenged to determine the linear calibration function relating force or displacement to voltages from the sensors. Concentrating on signals from the force transducer, students place weights on a mass cart which is held by a force transducer. In this configuration, the use of the transducer adds an extra challenge by requiring that students account for the mass of the cart that the weights are added to, without being able to directly measure the cart's mass. This essentially requires them to formulate and run two separate experiments to determine the gain and offset of the linear calibration function. Additionally, students must determine and represent their "trust" in experimental results through error analysis and prediction/confidence bounds (intervals).

In the second week of the Mass-Spring-Damper project, students use a motor as a displacement input, and they then use the sensors and to obtain the input-output characteristics of the system, again exploring DC and frequency (Bode) effects. In this case, the final goal is to characterize the spring and damper in terms of force vs. displacement, and to determine how the system responds to varying input frequencies. The concepts underpinning this material tie directly to their System Dynamics course, where the theory of the Mass-Spring-Damper is presented. This experimental process teaches the students to derive a result from two different styles of sensors, a skill that they will rely on in the IC Engine progression that they will later see. All results are captured in a worksheet deliverable that asks students to not only present their results but also explain and substantiate their findings using experimental evidence and error analysis. Students submit their deliverables in a pre-formatted worksheet which allows them to practice technical writing without requiring them to create an entire experimental narrative, a skill that has not yet been taught at this point in the term.

The Experimental Methods students next perform a 2-week vibrations project where they use a Laser Doppler Vibrometer (LDV) to characterize a fixed-free beam motion that is excited by a shaker. The device serves as a stand-in for an aircraft wing where an engine running at different throttle levels will cause varied excitation frequencies and could excite a natural frequency that might damage the wing. The lab challenges students to experimentally characterize a beam's frequency response in week one, with a focus on how to use and calibrate the LDV sensor. Using the LDV is not easy for novices; it requires the students to practice new skills, as useful results require integration of the output sine wave, which relates to velocities, to determine the position of the beam over time. This skill is important for us because the same type of integration is again needed in the IC Engine progression to determine energy over time as the crankshaft rotates under torque. The conclusion of this LDV experiment also provides students with the first challenge of writing a complete technical narrative report; having practiced presenting displays in the Mass-Spring-Damper laboratory worksheet, we now press them to consolidate their results display their understanding in a brief report that asks students to quantify uncertainty and to account fully for sources of uncertainty in the system and instrumentation.

For the third project in Experimental Methods, students next perform a 2-week stress/strain lab, where they again begin their work by calibrating a force transducer. This time students get a closer look at the problems inherent in force transducers by learning to understand the signal path of the transducer strain gauge measurement through Wheatstone bridge conversion from resistance to voltage to amplifier, filter, and finally signal acquisition with a myRIO microcontroller. Now the students fully characterize each component from an input/output standpoint, and they are asked to determine the expected calibration function and error of the force transducer. Students then confirm the function by performing a calibration on the entire force transducer; in this process, students learn to separate errors due to circuit path components from overall errors of the sensor (including material properties and other sources). In formal end-of project reports, students describe this separation of the effects of components by recommending which components should be upgraded to improve experimental results (reduce error) and which components have a negligible effect on the overall results.

This separation of component effects is central to the energy analysis students perform on the IC Engine later in the Systems Laboratory course. With the engine, students first determine a method of measuring energy (integration of torque over displacement), then determine friction effects, then given those friction effects they determine the inertia of the piston, crank shaft, and flywheel (with the engine head removed to eliminate compression effects). Finally, the engine head is replaced to introduce fluid (air) compression effects, and all the components from the earlier analysis are needed to model the full engine. While the separation of effects in the IC Engine project is more elaborate, it calls for the same skills that were practiced in the Stress-Strain project of the Experimental Engineering class.

The second week of the stress/strain block challenges students to use an error-prone displacement sensor along with their previously analyzed force transducer to test the stress/strain properties of several test objects, including an aluminum dog-bone, a climbing sling and three different grades of bolts. The focus of the analysis balances determining the error due to the device's limitations and the properties of the test materials, and establishing a process to determine whether the materials meet specifications. Students perform an in-depth error analysis to see how much they can trust the experimental test they perform (because of error-prone sensors, not student error), and by extension to see if the results they produce can be trusted as valid tests of the materials or if the entire system would need to be upgraded to provide an appropriate test apparatus. If the students suggest upgrades to the system, we ask them to explain how they would do this. This error analysis again practices skills that are pertinent to the IC Engine project, where students must fully understand each sensor in the system and how its behavior affects their overall understanding of the system.

The final project of Experimental Methods, acoustics, challenges students to extend their ability to perform tests from primarily looking at voltage values (amplitudes representing displacement or force) to seeing how time can be used as an output from a sensor. In the first week of the acoustics block students become familiar with their equipment and calibrate it by characterizing the speed of sound using a microphone and an extendable arm connected to an encoder. They learn how to process encoder data (time-based) to understand positions of the system at points in time, a skill they will leverage in the IC Engines project to understand the angular displacement and velocity of the engine crankshaft, based on signals received from a toothed-wheel sensor. The final speed of sound value is affected by the accuracy of the encoder, the accuracy of the timing of the microphone, and various amplification and signal processing elements. As before, students perform an in-depth error analysis, including looking at the signal processing elements individually, and by the end of the project, they can define not only how much the speed of sound measurement can be trusted but also how much of their calculated error is due to experimental devices (which could be upgraded) and how much is due to other effects.

During week two of this acoustics project, students develop and test a method of using sonar to detect the location of an object in 2 dimensions. This opens the students up to working with two encoders (angle and distance) and to looking at amplitudes and times in a repetitive acoustic signal. To reduce errors, students learn to gate the input and output signals, so the same test can generate multiple data points that can be averaged. As with the other Experimental Methods projects, this practice with gating and averaging is again in the IC Engines experience, since many of the properties of the IC Engine (eg. piston inertia effects, air pressure effects, etc.) happen within a single cycle. Using data from a single cycle would be highly error prone, but gating and averaging removes signal noise and other random errors to provide a more precise understanding of the system.

As they progress through the projects of the Experimental Methods course, students are also expected to gain increasing autonomy with their ability to run and report on experiments. By the time they perform the acoustics project, the lab materials provide little guidance at all; following that block students propose their own experiments, which they then run as their final lab. This final lab also carries a report where students must fully develop their own technical narrative to explain their experimental problem, experimental approach, conclusions, experimental justification for those conclusions, and an analysis of error to provide a level of trust for the conclusions. The quality of reports hugely improves throughout the course, which allows students to adeptly express themselves as they tackle more difficult challenges in the Systems Laboratory.

An In Depth Systems Laboratory

As does any introductory course, Experimental Methods introduces students to the fundamental problems of experimentation—setting up and calibrating instruments for data collection, comparing data to expectations, and quantifying uncertainty. Students become familiar with a variety of common sensors and analysis techniques by conducting projects that are carefully sequenced to introduce increasingly complex analysis methods in order to tease information out of increasingly complex systems. While the systems are simple and the analyses are constrained, the students leave this class with a set of skills that they will use in the follow-on course, Systems Laboratory. In that course, our students must use their data collection skills to study more elaborate mechanical systems using combinations of sensors and transducers. Specifically, this course requires students to:

1. Instrument systems of components to measure the system's performance,
2. Isolate and analyze subsystems to obtain useful system models,
3. Analyze their data to answer complex, open-ended problems.

Essentially, this second laboratory course calls on the skills the students developed in the first class, and applies them to more elaborate systems. This calls for students to solve problems that may seem familiar, but they find that studying systems poses several challenges in addition to the basic issues of instrumentation. Where the first course may have asked students to explore a component of a device, deducing information about system level behavior in a useful format (such as transfer functions of subsystems) requires an additional layer of consideration about the goal of the study, the available sensors and the conditions under which they will be used.

Additionally, in studying complex systems, we want students to understand which of the many available transfer functions may be useful for analysis or for control of the system, and we want them to learn how to carry out such analyses. In characterizing a DC motor, for example, it is not relevant or useful to fully characterize all components of the system when only a few elements are useful for controlling it. Students learn for example that they could analyze the electrical behavior of the motor by measuring armature current with an ammeter, but this is not useful if their goal is to control the motor's torque output.

Finally, when the students have determined what data to collect, and when they have appropriately wired a system to collect that data, we ask them to use that data to do real problem solving. As in the other course, the projects and the grading here are designed to prompt thinking and problem solving by nudging students in a productive direction and by focusing our feedback on assessments of their thinking, their ability to validate their conclusions and their ability to quantify uncertainty in their results. In our Internal Combustion Engine project, we may ask our students to "derive an energy model for an internal combustion engine"; in responding to this question, we expect students to think critically about how to define systems and subsystems, about which sensors to use to capture data, and which physics to bring to bear on the problem in order to create their model. In this way, we explicitly relate experimental skills to thinking, as we ask students to integrate all components of a laboratory project and then defend the conclusion that they draw.

An overview of the Systems Laboratory projects, with emphasis on an Internal Combustion Engine project, will illustrate how our students use the lessons learned in Experimental Engineering and how that learning prepares them to move from characterizing individual components to modeling a complex system. Systems Laboratory is a four-project course, with several multi-week projects. The first project focuses on basic experimental signal processing; this reviews the skills that were learned in Experimental Methods and reminds the students how to set up an experiment and how to obtain, analyze and explain data. Two further experiments, System Identification and Controls, engage students in obtaining data that can be used to make simple models of systems and then use those models to address real-world problems.

In creating system models for these introductory projects, students learn that by using the previously learned steps of experiment setup, sensor calibration, and data collection, they can use their data to synthesize system models that are useful in the real world. To this point in the term, we have asked students to use Newton-Euler analysis on the mechanical side of these system to create the needed transfer functions. However, once the students have gained familiarity with this method, we ask them to think more deeply about system analysis by introducing another way to do this—using energy based techniques, primarily the work-kinetic energy theorem. We do this in a multi-week exploration of Internal Combustion Engines, a project designed to integrate and reinforce all the lessons of our two-course laboratory sequence.

Our Internal Combustion Engines experimental setup is displayed photographically in Figures 3, 4 and 5. Figure 3 shows an overall view of the one-cylinder engine that students study, at the back of the photograph, plus related instrumentation surrounding it. Some of the single-use boards presented in Figure 1 can be seen at the front of Figure 3, with data cables clearly being connected to the computer at the left of the figure. Figures 4 and 5 present close-up views of the engine itself. In Figure 4, a toothed gear is visible on the left and a flywheel on the right; Figure 5 shows the toothed gear's connection to an encoder and its positioning near the two proximity sensors, which our students use to collect critical data.

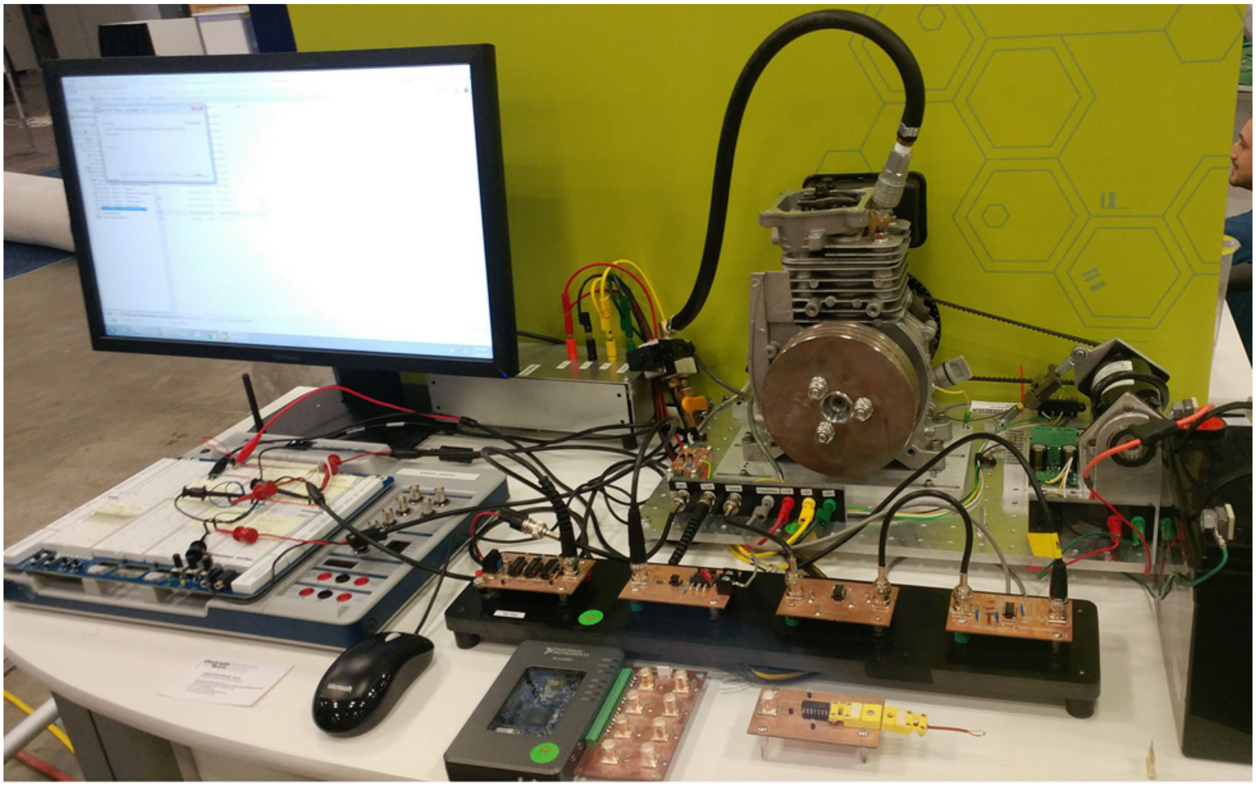

Figure 3. The Internal Combustion Engine project with associated electronics

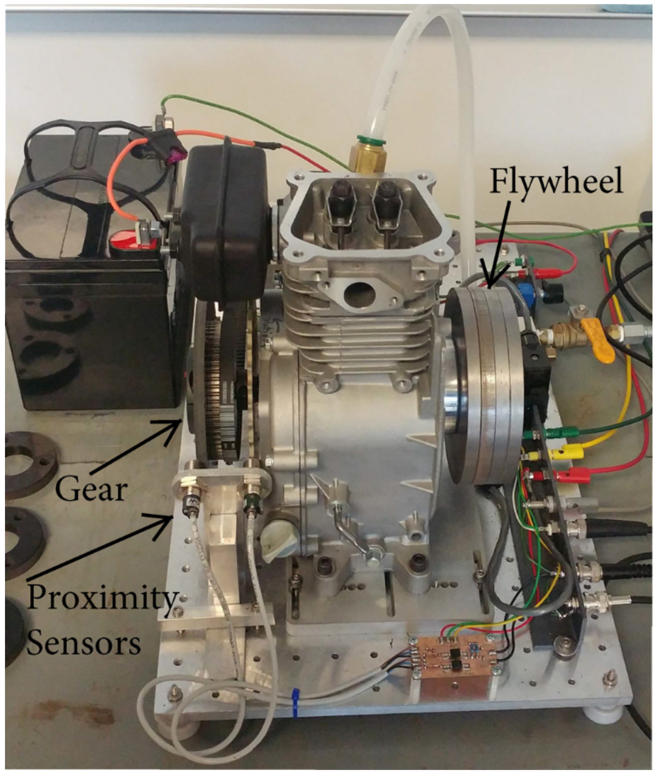

Figure 4. Front View of Experimental Setup

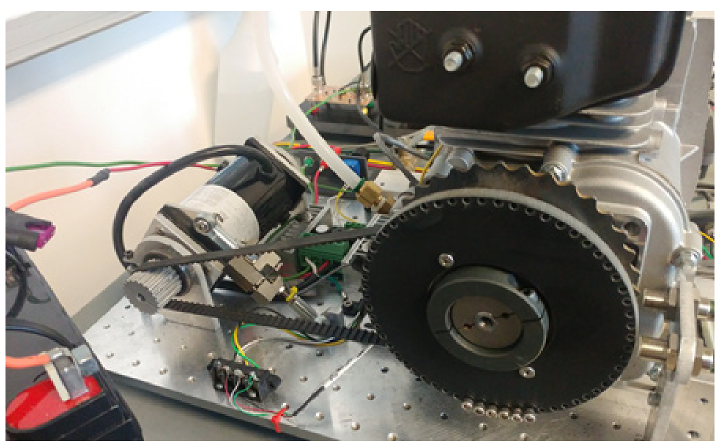

Figure 5. Side View of IC Engine Setup

Students perform a work/energy analysis on this engine to experimentally derive properties of the system. Sensors on the engine include a force transducer configured to measure torque, a proximity sensor configured to detect student-indicated angles (via bolts), and a proximity sensor coupled with a toothed wheel to detect wheel angle and angular velocity. From these measurements, students can determine piston and fly-wheel inertial effects, air pressure effects due to the piston motion, and energy transfer to and from the back-drivable motor/generator. On the input side, students can control the pneumatic valve open/close timing to drive the engine, or control fuel injector and spark plug timing to drive the engine under propane fuel.

In the IC engines project, students take data from three sensors in order to model the system:

1. A **force transducer** consisting of strain-gauges in a Wheatstone bridge configuration to measure torque output from the engine (indirectly, which is important to understand in later parts of the lab).
2. A **toothed-wheel sensor** for use in obtaining angular displacement and, through signal processing, angular velocity
3. A **cam position sensor** for use in both angular velocity measurements (as a redundancy to the toothed-wheel sensor) and in timing engine firing and control to specific moments during the 4 stroke cycle.

Understanding this instrumentation is a major tie-in to the material presented in ME 3057. The force transducer is of particular interest here, as our students used force transducers in several ME 3057 projects, so the force transducer characterization and calibration is both useful as a data collection tool on this project, and as a reminder of how to manage an experimental project. When the students have calibrated this sensor, they use basic FBD modeling techniques to relate the sensor output to the torque generated by (or imparted upon) the IC engine. This becomes the backbone of the more complicated modeling steps that come later in the lab. Furthermore, the students are asked to calibrate the sensor several times throughout the experiment, which reminds them that an instrument's outputs can vary with time (and often do) and shows the effect this has on data collection and analysis. This typically comes as quite a shock to students, who tend to think of "static" components like force sensors as completely time-invariant, when the reality is far different.

For this project, system identification involves calculating the rotational inertia of the flywheel and other spinning components combined. Students perform this operation by removing system components until they have isolated only a few terms in the system model, thus making this parameter easy to isolate in the work-kinetic energy formulation. Obtaining this inertia term allows them to calculate useful quantities later in the lab.

After this system ID is complete, students use the previously learned method of separating effects to perform data analysis that isolates the effects of different parts of the physical model. Based on this analysis, they then practice integrating the different data streams into a system model by powering the engine with compressed air and tuning it to achieve acceptable performance levels.

After the students have worked to tune the engine as a system, they then power the engine with a coupled DC motor and, using all that they have learned in this process, they calculate the amount of torque required to turn the engine, how much energy is lost to friction effects, etc. In this way, they again isolate the effects of different parts of the physical model that they have just manipulated. Through careful data analysis and processing, and they then use this understanding in the final part of the lab, which is powering the engine with compressed and air and again tuning the engine as a system to achieve acceptable performance levels.

In tuning the engine, the students must show that (a) the engine is putting out torque instead of requiring torque input to run and (b) they have achieved an optimal engine timing and configuration. This is all done by using the parameters, techniques, and analysis that we have been building in the previous experiment phases. By this point in the lab, students are familiar with how to look at the system output data and draw useful and intuitive conclusions about how the engine is performing. They can recognize strong performance vs. weak performance, and they understand how to tweak the system to affect change (positive and negative). By the end of this project, they should completely understand how to use their sensor output to inform engineering design choices.

Student Learning and Faculty Workload

The IC engine project illustrates how continuity between two courses both supports reinforcement of previously learned lessons and enables students to generalize those lessons for application at a different level of complexity. It is well known that students learn best when new information is clearly related to previously learned lessons [15]. Our Experimental Methodology course teaches students how to perform—and think about—experiments using single sensors and briefly, with two sensors. Our Systems Laboratory class extends those lessons by asking students to synthesize output from several different sensors—by asking students to think at a system level rather than a component level. Assessing the impact of the Experimental Methodology course on the students' performance in the Systems Engineering course is challenging. This is in part because we seek to evaluate the sophistication of the students' thinking, and in part because our only instrument for evaluation is the students' laboratory project reports. Because we seek to evaluate integrative thinking, we choose to avoid the style of point-allocation rubrics, as point awards necessarily skew towards simple report features that may fail to reflect the students' understanding of their work.

To reflect our emphasis on higher-level thinking we have chosen to develop mastery-oriented rubrics, where report sections are evaluated on a continuum from Novice to Mastery (or 1 to 5). This enables us to rank reports according to the students' ability to define critical points for each section of a report. Our generic rubric for a laboratory report is shown in Table 1.

Table 1. Default rubric for assessing student understanding in laboratory reports

Headed Section	Important Statement(s)	Evaluation Concerns (typical)
Introduction	Motivation and Goal	1. Does the Goal correspond to the Motivation? 2. Does the Goal pertain to the steps described in Methods?
Methods	Equipment and Measurements	1. How does the Equipment address the Goals? 2. Do the Measurements represent a strategy for meeting the goal?
Results and Discussion	Displays, Explanations and Uncertainty	1. Do the measured results correspond to the Methods? 2. Is Uncertainty quantified for results? 3. Are sources of uncertainty appropriately identified?

Headed Section	Important Statement(s)	Evaluation Concerns (typical)
		4. Do the result pertain to the goals? 5. Are the results persuasively defended?
Conclusion	Review of Points	1. Do the Conclusions review the results? 2. Do the Conclusions speak to the project goals? 3. Do the Conclusions synthesize the different measurements?

This mastery-oriented rubric can be employed across a spectrum of laboratory projects because it prompts for the essential parts of a project narrative while leaving flexibility as to the depth of thinking the student is expected to display. Third-year students may be novices at calculating and discussing uncertainty, while Fourth-year students might be held to a higher standard of understanding. And while format and clarity require comment insofar as they contribute to the evaluation concerns, this rubric subordinates those matters of design to our overall concern with students' understanding of how to conduct an experimental project.

Our laboratory changes are still in progress. While we are confident that our new approach is having a positive impact on student learning, the first cohort of students who have completed the Experimental Methodology course has only just begun the Systems Laboratory course. At the time of this writing, we are pleased with the reports that we have seen, but we have yet to compile and analyze a complete data set.

The revision of a laboratory sequence requires a good deal of effort in developing new projects and creating laboratory manuals and homework tasks that are coordinated with each other and with the overall mission of the course. Once these hurdles have been crossed, however, the course as we have implemented it requires little extraordinary effort. We meet with our TA staff twice a week; on Monday mornings the staff rehearses the week's project, and the TAs create their own data sets, which they can use as reference points when they review their students' progress during the student lab sessions.

We also meet to discuss grading with the TAs on Fridays when students submit lab project reports, and these meetings and these grading meetings call for some additional faculty input. We spot-check student reports as they are submitted, and we select three example reports for presentation to our TAs for grading calibration and policy review. We select these examples carefully, as they should display the range full range of quality in the week's submissions. We sanitize them, removing students' names and section numbers, and then we distribute the examples to our TA staff in advance of the Friday meeting. At these meetings, we ask the TAs to evaluate each example report, to outline comments that should be made and to rank the examples according to our criteria, as outlined in the default rubric of Table 1.

Preparing for these Friday calibration meetings can involve a good deal of faculty energy, as numerous submissions must be checked and evaluated, and reports that reasonably characterize "mastery," "average" and "novice" report quality must be selected and prepared for presentation. As a follow-up to the discussion of report quality, faculty time can also be spent spot-checking the graded reports for comments and for consistency with the conclusions reached during the Friday meeting.

Conclusion

We have presented an overview of a newly redesigned sequence of laboratory courses to show how laboratory courses can be modified to better promote learning. We also show how this approach can be scaled across the sequence to accommodate the increasingly sophisticated projects the students should encounter as they move through their program. While adopting this approach to laboratory instruction does appear to require additional time investment for the instructional team, we hope to soon demonstrate that this investment generates improved student learning outcomes.

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