

## **Optimizing Efficiency and Effectiveness in a Mechanical Engineering Laboratory using Focused Modules**

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# Optimizing Efficiency and Effectiveness in a Mechanical Engineering Laboratory Using Focused Modules

## Introduction

Laboratory experiments are a mainstay of undergraduate engineering education. Instructional laboratories are used to satisfy a number of learning objectives, and they are often used as a vehicle for assessing ABET student outcomes for design of experiments, solving engineering problems, and using modern tools of engineering as well as other outcomes that are more distant to the experiments themselves; e.g., teamwork, professionalism and ethics, life-long learning, and especially communications. This paper will describe the process of redesigning a junior-level mechanical engineering laboratory on measurements and instrumentation at Georgia Tech. Such classes are fairly standard in ME curricula, and they are often structured so that a new measurement technique, or new sensor/actuator is introduced in every lab. Such courses have the advantage of introducing students to a wide variety of instruments and measurement techniques, but they do this at the risk of losing conceptual connections between the weekly projects. This potential problem was compounded by the original format of the labs, which suffered from having large numbers of objectives and activities that were not well integrated. Finally, to accommodate the need for efficiency in our large program (approximately 300 students per semester), the individual lab projects had become procedure-oriented. Confronted with many different types of labs, equipment, deliverables, and styles, students became dissatisfied with the course, complaining about the workload and questioning the importance of what they were learning.

The redesign of the laboratory course was primarily motivated by a desire to increase the inquiry-based aspects of the lab and to de-emphasize and/or eliminate rote procedural formats that characterize many lab classes. The redesign was grounded in the theory of cognitive load, in particular, managing the cognitive load so that the ratio of germane cognitive load to extraneous and inherent cognitive load was maximized (Smith and Kosslyn, 2006). This involved several efforts: 1. Pairing down the number of tasks in each laboratory session, keeping only those with highest value, 2. Developing new formats for deliverables that emphasized higher levels of knowledge, 3. Structuring topics into two-week blocks. The latter point is highly important since it decreases the number of new topics that are introduced, but it also allows students the opportunity to think more deeply about the subject matter before moving on to dissimilar topics. The depth of exposure is highly correlated with the students' ability to reach higher levels of understanding as depicted in various knowledge taxonomies (Shavelson, et al., 2005).

## Background

Much has been written about the nature of engineering labs. As technology changes, many papers have focused on the opportunities to incorporate new sensor technologies, data acquisition, or real-time control. The incorporation of new technologies does not always result in labs that are more sophisticated. Counter-intuitively, the availability of new measurement tools and software can sometimes make difficult concepts more accessible to students.

As new opportunities emerge, the bigger question concerns how labs should be structured to elicit deeper levels of learning. For example, several different taxonomies of learning are relevant to a laboratory environment. Bloom's taxonomy and its extensions and variations are

very popular and are applicable to both laboratory and traditional lecture setting (Bloom and Krathwohl, 1956; Krathwohl, 2002). The six original levels proposed by Bloom were Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. Another decomposition, attributed to Shavelson (Shavelson, et al., 2005) posits four different types of knowledge: declarative knowledge (“knowing that”), procedural knowledge (“knowing how”), schematic knowledge (“knowing why”), and strategic knowledge (“knowing when, where, and how our knowledge applies”). This framework provides a useful way of evaluating laboratory experiences; what is typically termed “inquiry based laboratory exercises,” are ones that reach the higher levels of the knowledge taxonomy (Koretsky, 2011). Pre-labs and other types of preparation are also important as identified in Kolb’s experiential learning cycle (Kolb, 1984; Abdulwahed and Nagy, 2009). Chi has proposed a new formalism in active learning, which is relevant to laboratory and other forms of hands-on learning (Chi, 2009; Menekse, et al., 2013). Her taxonomy is termed ICAP, which is an acronym that orders learning activities from most active to least active: interactive (I), constructive (C), active (A), and passive (P). The ICAP hypothesis predicts that as student engagement of learning materials increases, learning will increase. What the three taxonomies of knowledge have in common is that they build on one another- properly scaffolded learning experiences can take advantage of this natural progression of understanding.

Clearly, the assertion that all hands-on learning is effective in teaching students new concepts is not true. Mundane laboratory experiences and laboratories that are highly procedural are not conducive to students thinking deeply about what they are doing and why they are doing it. In particular, Shavelson’s third and fourth levels of knowledge, schematic and strategic, are not reached unless students are forced to apply their acquired knowledge soon after being exposed to it. Once the knowledge reaches these higher levels, students are able to internalize it and build on it, especially if the knowledge is reinforced with touch, sight, and sound (Ferri, et al., 2016)

Students perceive that inquiry-based laboratory experiences are more beneficial than traditional ‘cook-book’ labs. Flora and Cooper (2005) found that students in an inquiry-based environmental engineering lab reported a more enjoyable experience than a traditional lab, though no evidence was provided indicating students learned more effectively in their immersive inquiry environment. Other studies have also shown improved student attitude concerning inquiry-based labs (Allen, et al., 1986; Berg, et al., 2003). Deters (2005) provides further insight by recording positive and negative student comments regarding an inquiry-based high school chemistry course. Shared negative comments lamented an increased effort required by students and also expressed trepidation concerning being in control in the laboratory. On the other hand, positive comments indicated that students perceived an increased ability to correct mistakes, explain outcomes, and communicate more effectively; however, these conclusions were not validated or quantified, as students merely believed they learned more in an inquiry-experience. In a different survey of student opinions, Allen, et al. (1986) highlight that even though students may think the inquiry labs are more difficult they also perceive the inquiry labs to be more interesting and better at developing analytic thinking skills.

Inquiry-based laboratory experiences also result in increased quantitative understanding of the course material. Lord and Orkwiszewski (2006) implement inquiry-based methods in a college biology lab, where students were asked to develop a laboratory to investigate osmolarity. The

results were compared to a control group which performed the original lab, and it was found that on average students not only better enjoyed the inquiry lab, but also scored slightly higher on a post-lab quiz. Gormally, et al. (2009) showed that students who participated in an inquiry-based introductory biology course demonstrated more improvements in science literacy and research skills when compared to peers who enrolled in a commensurate traditional course. Interestingly, the students in the traditional course were more likely to have more confidence in the subject area than the inquiry students, though the inquiry students were more likely to correctly ascertain their competence.

Once an instructor decides to redesign laboratory experiences to make them more inquiry based, there is a risk of going too far. Rather than making the experience more challenging and interesting, the students can become discouraged and can disengage from the effort. Indeed, there is some disagreement about the efficacy of inquiry-based learning (Kirschner, et al., 2006, 2013). Students enjoying the experience does not necessarily translate into a long-term change in memory (i.e., learning). It is hypothesized that inquiry-based laboratories violate the premise of human cognitive architecture; when students are expected to form their own opinions and draw their own conclusions as in inquiry-based learning, they lack sufficient connections between the working memory and the long-term memory. Several recommendations are made to avoid inquiry-based laboratories conflicting with established cognitive learning theories (Bruck and Towns, 2009):

1. Laboratory curriculum should be scaffolded across every level, involving theory background, laboratory instrumentation and methods, and even inquiry itself.
2. Laboratory curriculum should gradually progress from traditional methods to methods involving more advanced inquiry skills.
3. Student performance should be assessed throughout the implementation of an inquiry-based laboratory.

In this paper we describe the redesign of a traditional engineering laboratory course in order to accommodate these recommendations.

### **Our Approach**

Our junior-level measurement and instrumentation laboratory course had over many years come to emphasize post-lab results analysis, while the students' time in the laboratory was governed by elaborate instructions that detailed what data to collect and how to use the instruments; students' post-lab activities were dominated by data analysis and report preparation. Students disliked this lab class, and it was unclear what skills they retained from their experience.

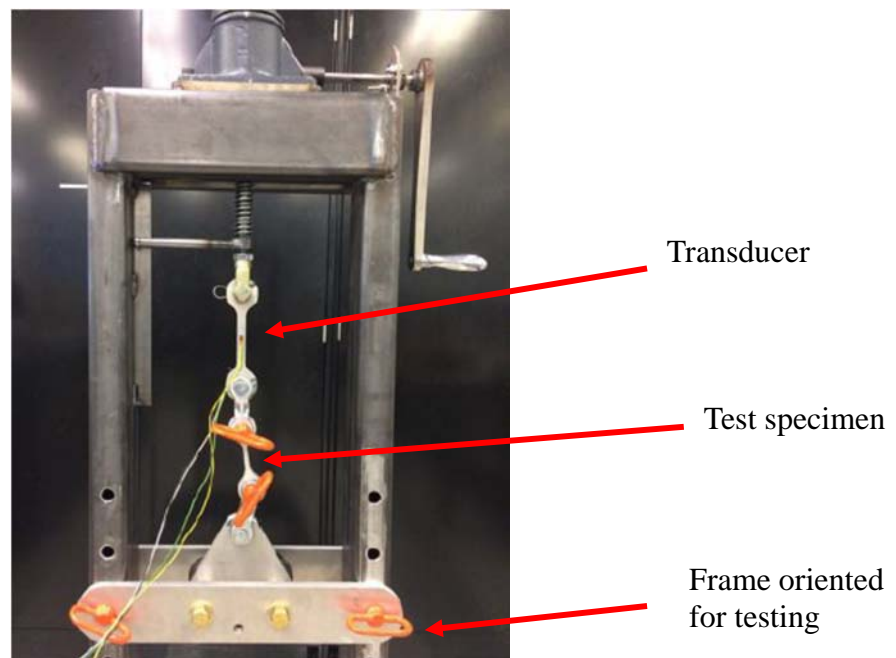
To change this class, we chose to design experiences that were less dominated by instructions and analysis, emphasizing instead hands-on learning. Specifically, we decided that students needed above all to learn how to set up and calibrate instrumentation and to account for uncertainty in the data that they collect with their experimental setups. Consequently, we developed variants of our existing labs, dispensing with much of the analytical and modeling work from the previous version of the course, focusing instead on the students' ability to develop and calibrate a data collection setup for the project at hand.

Our focus on the students' ability to instrument a project was aided by the introduction of LabVIEW equipment, including ELVIS Boards and myRIO devices. Using these we have been able to develop realistic instrumentation exercises that allow students to learn and explore the systems and instruments under study before they are asked to collect data from the real tools. In this way, we are able to replace detailed instructions with exploration while suffering no penalty in time or broken equipment. Yet we do not replace real-world testing with simulations; rather, we are replacing over-emphasis on procedures with training in data collection as a necessary first step in the students' exploration of their projects.

This lab redesign has numerous features, to include writing instruction, intensive training and oversight of a large staff of teaching assistants, and of course, redesign of crucial projects. These elements of the redesigned course are described next.

### **An Example Project**

To illustrate our modified approach to laboratory instruction, this section describes a stress testing project that we introduced during summer and fall of 2016. Any instrumentation project requires students to first understand the data collection methods being used and second to understand the mechanical system that is being examined. In our new two-session approach, the data collection system is teased apart from the details of the system being examined in order to involve the students intimately with their equipment as well as with the mechanical system itself. To understand the data collection system, students spent one full lab session creating and calibrating a force transducer; to understand the mechanical system under study, students spent a second lab session using their force transducers to test a number of objects to failure.



**Figure 1. The test frame, with the student-created transducer attached to a test specimen.**

To make this an inquiry-oriented project, we created a hand-operated stress-strain testing frame that would enable students to gain hands-on experience with stress testing and that would enable them to create their own instrumentation. The test frame is shown in Figure 1.

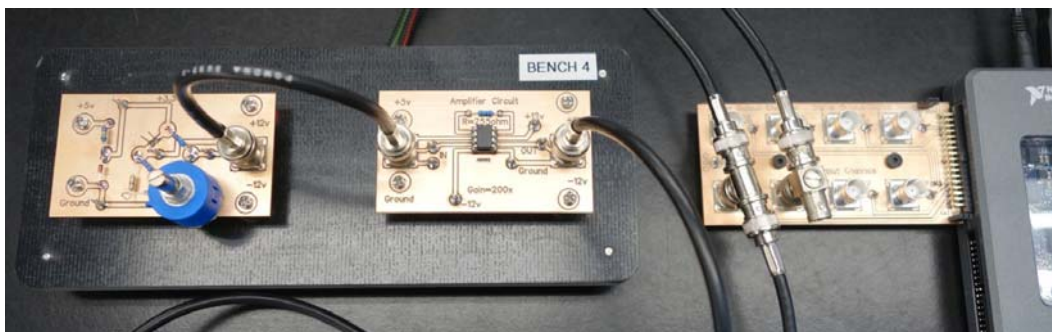
This is a hand-cranked testing apparatus, enabling students to intimately observe the changes in a material as they impose stress on it. As in this photo, the students are testing an aluminum test specimen. Above the test specimen is a dog-bone aluminum piece, to which a strain gage has been attached; this is the transducer that the students use to collect data on the aluminum test specimen, with output delivered to an amplifier, a Wheatstone Bridge, and finally to both an oscilloscope and a myRIO, driven by National Instruments LabVIEW.

During the first session of this two-session lab project, students build their data collection system. They are provided an aluminum dogbone and a strain gage; from these they are required to create a stress transducer by sanding the dogbone, cementing the strain gage, and attaching wires, as in Figure 2.



**Figure 2. Students attach a strain gage to an aluminum dog-bone and solder wires to the leads.**

They then must calibrate this by attaching the transducer to the test frame, affixing weights, and attaching the output wires to the Wheatstone Bridge circuit, as in Figure 3.



**Figure 3. Wheatstone Bridge, Amp, and Circuit board with myRIO connections.**

In traditional lab projects, much of this work is invisible to the students, but we choose to expose students to the lowest levels of the data collection systems that they might encounter. Instructors

and Teaching Assistants provide guidance and oversight for students as they test their materials, but they are responsible for understanding their equipment well enough to calibrate their data collection system. This can be a slow process, as introductory students often learn by making mistakes; we strive to accommodate those mistakes while offering enough in-person guidance to prevent frustration and disengagement.

Students began the second session by recalibrating their force transducers to limit experimental error, and then verifying the manufacturer calibration of a magnetic displacement sensor connected to the testing frame. The magnetic displacement sensor is not a direct extensometer, which would typically be used in these applications, but it is easier for students to work with, is less likely to fail when used by novice users, and allows students to analyze the experimental error of the system as a whole when experimental measurements are compared to theoretical results. Students have access to calipers to measure strain directly during the experiments, should they choose to do so. Students who take this initiative are rewarded with extra credit.

Students then used the transducer and their data collection system to test to failure three bolts, a small aluminum dog-bone, and, time permitting, other objects that the students were invited to bring in for examination. Because the test frame is hand-cranked, students were able to control the speed at which their test specimens were brought to failure. This allows them to observe and to plot Young's modulus, the yield strength, ultimate strength and failure, and it enables them to obtain tactile feedback at each key point in the text, such as the decreasing force required after necking begins.

Our students found this project to be challenging, but they also found it to be exciting and engaging, as reported in our end of term course evaluation surveys. As we gain data from more repetitions of this project, we hope to develop outcome comparisons with more traditional versions of undergraduate materials testing projects.

### **Training for Teaching Assistants**

A fundamental tenet of inquiry is that the instructor guides the student to conclusions, which would be deemed acceptable within the discipline. A more esoteric consequence of this teaching style is that learners are assessed on how they think, as opposed to traditional methods that reward correct answers. Synthesizing these two points, it is evident that inquiry-based laboratories require experts to create, administer, and assess. Unfortunately, the requirement for expertise is directly contradictory to the current atmosphere in science education at large research universities. Luft et al. (2004) provide an excellent discussion of TA culture in the sciences, and summarize the issue by stating:

“Ultimately, graduate students may even be told by their advisors that research should be a focus, and that teaching assistantships should not be held for multiple years because this will jeopardize their careers...Unfortunately the culture in which GTAs exist places them in a situation that is wrought with tension and difficult to change.”

In light of this observation, it is unfortunate that inquiry-based laboratories often require more effort and expertise from teaching assistants and instructors. Gormally et al. (2011) note that the fundamental building block of inquiry labs, the process of guiding questions, is significantly

more difficult for new TAs and instructors. To remedy this deficiency they suggest training workshops focused exclusively on implementing inquiry in the laboratory, in addition to continual feedback and accountability from more experienced instructors. The dearth of training for TAs is evident across the sciences; Golde and Dore (2001) show that only a third of TAs in the sciences had participated in a TA training program. Stewart et al. (2013) carefully analyzes the progress of an inquiry-based astronomy lab, observing that TAs were often given little instruction in how to interact with students, and consequentially, students often completed labs easily without TA assistance. Volkman and Zgagacz (2004) provide teaching assistant opinions of an inquiry-based learning physics course, where the instructor recommends that “new graduate teaching assistants should be required to participate in a preliminary observation semester, and during the first teaching semester, graduate instructors should enroll in a concomitant seminar class that examines science teaching and learning and the nature of science.” The lack of training for TAs when implementing inquiry-based labs is lamented by many other authors (Luft et al., 2004; Volkman and Zgagacz, 2004; Kurdziel et al., 2003; Marbach-Ad et al., 2012; Bruck et al., 2010). Bruck et al. (2010) emphasize the importance of faculty members’ engagement, and find that without it, “the quality of the curriculum suffers, TA training is limited, and students may exhibit a lack of preparedness.”

Several recommendations can be made for mitigating these problems:

1. A weekly course-specific training program should be provided to familiarize TAs with course material and current teaching methods. (Marbach-Ad et al., 2012)
2. A training program should be provided at least once per semester to teach TAs proper teaching methods for using inquiry in the laboratory (Kurdziel et al., 2003; Bruck et al., 2010)
3. Faculty members should be engaged in the course to develop materials and methods, and hold TAs accountable for their teaching strategies (Bruck et al., 2010).

We have acted upon these recommendations by creating a training and mentoring program that includes weekly mentoring and grading guidance as well as consistent faculty participation in our lab courses. The details are these.

At the beginning of each week, we gather our TA staff in the lab and supervise them as they perform the tasks that the undergraduate students will perform under their supervision. This experience provides the TAs with practical familiarity with the equipment and the instructions that the students will use, and it enables the instructors to demonstrate to the TAs how to work with students in a lab session. We give general advice, we demonstrate how to ask leading questions, and we direct the TAs to useful resources, just as we want them to do with the undergraduate students.

On Fridays, we conduct grading / norming sessions during which TAs will grade student lab reports under the supervision of the technical instructor and the writing instructor. In these sessions, TAs are expected to provide scores and feedback that will be consistent across the dozen + sections of our course. More important, by constraining the grading time, we expect to concentrate our grading and commentary on the thinking-related components of the student reports, in contrast to the format-driven commentary that is commonly seen when grading staff



has more time to spend with each paper. In this way we teach our TAs to identify the points in student writing—or professional writing—where central ideas are presented.

To assure that the TAs are concentrating on thinking rather than format, we open these grading sessions with a model exercise where we present student work—on the project at hand—that we have marked with regard to substance and to format—teasing these apart in a way that will save time and allow focus on substance. The result of this ongoing program is expected to be that the TAs will become better scientific communicators and better instructors. We expect this to stay with them throughout their careers.

### **Accommodations to program size**

At Georgia Tech, the size of this course currently ranges between 250 and 300 students per semester (and growing). This presents challenges which have historically pushed faculty toward “cook-book” or highly prescriptive and detailed procedures to avoid equipment failure and to ensure all students get all needed data during the limited 3-hour lab session. The lab room accommodates 18 students, and up to 18 lab sections are currently required to run the course. When we add the additional 3-hour block for TA training Monday mornings and an equipment set-up block Friday evening, this means the lab is in constant operation Monday – Friday 8:00am – 10:00pm. This leaves little time for equipment repair, and makes it impossible for a faculty instructor to lead all lab sections.

We have addressed the equipment repair challenge in three ways:

First, we over-designed all new equipment to handle the abuse of novice users. This does not equate to eliminating student failure by using hands-off closed-systems, but rather over designing the strength of sensitive components and having designed failure points that allow students to recover from and learn from set-backs and then allowing them to repair the system quickly without delaying their overall progress.

Second, all equipment was designed to be modular and fully interchangeable. This allows any broken component to quickly be quickly swapped with a functional component in any experimental setup. In most cases, when failures do occur, this modular scheme can allow the experimental device to be repaired quickly by either the student or a TA.

Finally, we set-up and maintain 10 experimental lab stations even though only 8 are ever planned for use during any lab section. In the case of an equipment failure that cannot be quickly repaired, groups can be shifted to a back-up lab station without delaying their overall progress. The original device can then be repaired even while active labs are running. This has the added benefit of allowing for two “open-hours” stations that students can use either to explore in advance of lab (getting ready for lab) or after lab for their own experiments or to verify a reading, take pictures, etc.

These three methods have significantly reduced the workload of lab maintenance staff, and allowed labs to run much more smoothly than was the case in the past.

## **Communication for students and Teaching Assistants**

Reporting, as everything else in our lab redesign, is driven by our desire to cultivate thinking instead of instruction-following. Most programs require students to submit experimental results in written reports, and in the last 20 years or so, many departments have addressed ABET's communication criterion by integrating some degree of formal writing instruction into their laboratory classes. We have carried this focus on writing a step farther by fully integrating communication instruction into the design of the projects and the training of the Graduate Teaching Assistants who staff the course.

Under this approach, we differentiate the report submissions and grading expectations according to the amount of initiative that the project requires of the student. For introductory projects, our goal is for the students to learn the basic steps of setting up an experiment and collecting data; the students are not asked to motivate early projects or design experiments until they have mastered these important technical skills. While students are learning the rudiments of data collection, we require them to submit their results as responses to prompt questions on pre-prepared worksheets. Each question prompts the students to present a display of results (allowing us to grade format) and a paragraph-size explanation of that result, which is to include prompted comments on the system under consideration (required) as well as commentary on whether the obtained results resemble the expected results (to establish whether the students understand what they are looking for). Further commentary would explain what factors influenced the results to be non-ideal (which would indicate understanding of both the system under study and the data collection system at issue in the lab). Grading reflects mastery of the experimental system—the more the student explains, the better the mark.

As the students master the details of project set-up, we shift to more formal reporting, with short reports that ask for project motivation, goals and methods as well as results, and we support this by providing examples and by providing lectures on the structure of and rationale of formal reports. Project motivation and goal statements can be confusing and disruptive when they are applied to projects that are designed to promote experience rather than to experimentally tackle a problem. We request formal reports only for those projects where students have been given a general question to address but are given some freedom to design their experiments in response to that question. In these cases, by controlling the goal and the equipment, we strike a balance between cook-book control over the project and the too-much freedom that would make fair grading impossible. As we grade such reports, we seek evidence of mastery more broadly in the student reports—a methods section should explain how the students relate the project goal to the equipment available, a results section, because we have taught results on the worksheet project, should be routine, and a discussion section should provide benchmarks to which the results are compared for validation purposes.

As a final, open-ended project, we ask students to propose an investigation of their own. Following lectures on project design, identifying benchmarks and preparing proposals, we gave them this task: Constrained by the equipment that we can provide and the place(s) where data can be taken, the students are to propose a data collection project of their own, for bonus points. Under a 2-week time limit, the student teams will propose in a homework submission of 2 pages, a data collection project of their choosing. They will submit these as written exercises, for grading, and our grading will assess these like real proposals—we will determine whether the

project is interesting or novel, whether the goal is well defined, whether the data collection plan is feasible with the equipment available, and whether the results benchmarks have been effectively identified. Student proposals that pass this screen will be allowed to go forward—meaning that the students will be permitted to perform their projects in our lab over a 2-week open lab period. Those students who opt to perform their experiments will receive bonus points for the course.

### Feedback from students

To assess our course redesign, we first compared student course evaluation scores for the modified course with recent scores for the course before changes were implemented. These scores are shown in Table 1, which shows that the student workload was somewhat reduced in the revised course, but that the students found the revised course to be otherwise somewhat more challenging.

Table 1: Student course evaluation results for pre- and post-modification terms

	Spring 2016	Fall 2016
Workload, Hours per Week	10.35	9.08
How prepared to take subject (1 = Completely unprepared, 5 = Extremely well prepared)	4.27	3.73
Amount learned (1 = Almost nothing, 5 = Exceptional amount)	3.54	3.48
Assignments facilitated learning (1 = Very poor, 5 = Exceptional)	3.84	3.61
Assignments measured learning (1=Very poor, 5 = Exceptional)	3.49	3.37
Overall course effectiveness (1 = Strongly disagree, 5 = Strongly agree)	3.74	3.61

We can gain resolution on this mixed result by examining the results of an end-of-term survey that was conducted in the Fall 2016 offering of the course. This survey focused directly on the students' satisfaction with the modified lab format and compared it with the more traditional, instruction-driven lab class format. Students used a 1-5 scale, where a score of 5 mean "Excellent" and a score of 1 means "Needs Improvement." Table 2 shows student reviews of the new-format labs in row 1, and reviews of older-format labs in row 2. In row 3, students compared the two formats, indicating their preferences for one over the other.

The results in Table 2 are clearly mixed. Rows 1 and 2 indicate that our students somewhat prefer our older, instruction-driven lab projects to our newly-developed, exploration-oriented projects. In row 3, responding to a more generic question about project format, student preferences are narrowly split. We account for these responses by examining short-answer responses that were integrated with the numerical survey. These short answer responses enable us both to identify student concerns and to correlate their comments with their numerical responses.

In a hand-review of the student responses, we identified terms that related to student workload, understanding, interest / excitement and frustration with logistics, and we found that these terms were used consistently to describe the two formats that the students were exposed to. The newer, exploration-oriented labs were consistently positively described as *interesting, hands-on, and good learning experiences*, while complaints indicated that these projects posed logistical drawbacks in the laboratory, as *equipment was often balky or in short supply*. In contrast, the more instruction-oriented projects were positively described as having *clear instructions, reliable equipment, and easily understood tasks*.

Table 2: Student Comparison of New and Traditional Lab Formats

		1	2	3	4	5
1	Rate the quality of the New-format labs (5 means Exceptional and 1 means Needs serious improvement)	18	51	89	97	16
2	Rate the quality of the Old-format labs (5 means Exceptional and 1 means Needs serious improvement)	1	23	79	117	49
3	Which lab format do you prefer? (5 means the new format, 3 is Neutral, and 1 means the Old format)	62	35	62	44	59

It is important to note there is little overlap in these comments save for discussions of equipment. Students who provided narrative answers appeared to welcome the challenges presented by exploration-oriented projects, but they desire clarity in the management of these projects. Fortunately, many of the complaints received from students can be addressed relatively easily by refining and clarifying the supporting instructional material.

### Impact and Consistency with Senior Laboratory

At Georgia Tech, students who have completed the junior-level measurement and instrumentation class go on to take the senior laboratory. The senior laboratory is a required, 3-credit hour course with two hours of lecture and three hours of lab each week. While the focus of the junior-level class is on measurements and instrumentation, the senior-level class focuses on “systems,” and in particular on how theoretical models can be used to explain and predict experimental observations. Hence the title of the class is ME Systems Laboratory. To avoid using the course names/numbers, the two lab classes will be referred to as the “measurements lab” and the “systems lab,” respectively.

The systems lab currently consists of approximately six experiments on mechanical systems and six experiments on thermal systems. The weekly experiments are supported by one or two lectures in which the theory and models for the week’s system are reviewed. The students

perform a scripted, step-by-step procedure, and then compare their experimental results to the theoretical predictions. On the thermal side, examples of one-week labs include thermal radiation, major loss in a pumping system, and forced convection. On the mechanical side, one week experiments involve acoustics, two-degree-of-freedom vibration absorbers, and controls. The controls lab can be viewed as a two-week experiment in which the first week is spent on system identification, and the second week on feedback control. Other than that, most week-long experiments do not relate strongly from one week to the next.

Similar to the measurements lab, students were highly critical of the systems lab in online course surveys and in exit surveys from graduating seniors. Students cited several shortcomings. The first was that there was a perceived redundancy from the material in the measurements class and the systems class; the instructors of the two courses were not fully aware of the content of the other class, so there was a lack of visible continuity and organization between the two courses. Students also found the highly procedural lab experiences to be uninspiring, and they could not see the direct applicability of the concepts to real world engineering tasks. But the bigger complaint was that students felt that there was insufficient time to really understand a topic before they were required to prepare their reports and move on to another topic. Faculty also wanted students to see more realistic, multi-disciplinary problems where it is necessary to spend sufficient time on each component that makes up the system.

To address the student perception issues, a decision was made to revise the structure of the senior lab from two to one in which there were twelve one-week experiments, to one in which there would be a much smaller number of multi-week experiences. The multi-week experiments would be scaffolded so that each week built on the last, culminating with a fairly sophisticated investigation of a system having multiple components. Each multi-week experiment would give students time to reflect on their results and, when necessary, redo experiments. The multi-week experiments would be spaced with one week in between to give time for written and oral presentations of findings.

Clearly the format of the measurements lab has been instrumental in the revision plan for the systems lab. The two-week experiences of the measurements lab have demonstrated the advantages of giving students more time on a topic, and stripping away some of the extraneous cognitive load that comes with starting new topics each week. The new structure of the measurements lab also highlights a “less is more” mentality, grounded in the belief that it is misguided to think that a single course can teach the usage of every type of sensor or actuator. If students learn the fundamental principles of experimentation, the belief is that they will be able to transfer that knowledge to other applications if and when they need to. In the same way, looking at a smaller number of sophisticated systems in the senior-level class gives students confidence that they can tackle harder problems after graduation.

### **Conclusions:**

Inquiry-based education in the laboratory is difficult to conceptualize, develop, and successfully implement. As the previous review indicated, even the definition of inquiry can be convoluted, ambiguous, or misconstrued, due to differences in the type of inquiry under consideration. These types of inquiry vary widely in their objective, reaching from traditional “cookbook” laboratories

to truly open-ended experiences where students select the problem and procedure, and subsequently draw their own conclusions. In addition, implementing these concepts on a large scale requires significant investment from students, teaching assistants, laboratory coordinators, and faculty members. Assessment of any inquiry-based laboratory course must not only involve qualitative and quantitative results, but should also be capable of distinguishing between factual and conceptual information learned. In general, the experiences, thoughts, and conclusions gleaned from the previous literature can be summarized in several major points:

- The objective of the course should be first established before embracing any single pedagogy or learning tool.
- Any pedagogy or learning tool must appeal to the science of learning; i.e., human cognitive architecture.
- An appropriate level of inquiry should be selected, ranging from traditional labs to open-ended labs. The level of inquiry is constrained by personnel resources, class size, and institutional constraints.
- Sufficient training should exist of TAs, including course material and the science of learning. Relatedly, faculty members should be invested in this process to establish accountability.
- Many of the examples mentioned herein which successfully applied inquiry to the laboratory required a significant level of time to develop, implement, and modify; thus, all parties involved must be invested in the concept and practice of inquiry-based laboratory education.
- Methods must exist for assessing student performance in regard to previously-established course objectives. Course grades and student enjoyment, though useful, are not commensurate with assessing student performance.

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