Models of Mobile Hands-On STEM Education

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Abstract

Hands-on activities can improve student understanding of STEM topics dramatically, and laboratories are the most common implementation of hands-on learning. However, most experiments are performed in dedicated laboratories, which may be costly and inaccessible to students, and the labs may not be timely with respect to when students learn the associated theoretical concepts. Mobile hands-on labs are ones that use equipment that is affordable and portable, so that students can own the equipment and do the labs anywhere anytime. This paper presents three models of implementation of mobile hands-on education: a limited number of small, in-class labs given in lecture-based courses; full-scale labs done on student-owned equipment; and studio classes. These models were all implemented in Electrical and Computer Engineering programs, though the modules are also used in K-12 outreach activities.

1.0 Introduction

Hands-on activities are an essential part of the learning experience for STEM students to demonstrate theoretical concepts in practice and to connect students with the experimental component of our STEM disciplines. Historically, these activities were relegated to structured experiments conducted during formal lab courses in limited access, centralized laboratories utilizing expensive equipment and requiring extensive support infrastructure. Portable, low-cost, experimental platforms that utilize student resources such as laptops and other mobile devices allow for **ubiquitous hands-on experiences available to students** anywhere and anytime: at desks in a traditional classroom, in a dorm room, in a study group setting, at a coffee shop, etc. These types of experiments allow for a new pedagogical model that promotes a more complete integration of theory and laboratory experience. This new paradigm opens new avenues for inquiry-based learning that will enhance and deepen student learning of fundamental concepts, experimental concepts and skills, and give them experience in system level design and integration.

Imagine mobile hands-on learning activities that involve both the student and the faculty member in the learning process without considerable time or effort by the instructor. And, suppose that there are freely available resources to assist a faculty member, educated under the old lecture system, to introduce hands-on learning modules and rapidly develop his or her own modules using validated procedures. Now, let's consider what would happen if this pedagogical approach is integrated throughout a STEM curriculum so that students see how concepts from one course can be applied in other course to build a system-level understanding of their discipline and how theory and practice are used in the design process. Suddenly, we have STEM graduates who know, and appreciate, the complexities of their discipline and who are able go out into the workforce and immediately contribute to product development.

This paper summarizes current models for delivering mobile hands-on education in engineering, including in-class labs, labs done at home, and mobile studio classes. The authors of this paper come from three different institutions, each having an NSF grant on mobile hands-on education in engineering and each using a different model of delivery. The generic aspects of these models are discussed along with a discussion of the best practices in each model; evidence of the success of the different approaches are included.

2.0 Models of Deployment

This section discusses three particular models of implementing hands-on activities in a curriculum: small in-class activities in lecture-based courses, student-owned equipment in lab courses for students to complete at home or at school, and mobile studios where the hands-on activity is fully integrated into a lecture class. The level of commitment for students and for instructors differs for these different models.

2.1 Small In-Class Activities in Lecture-Based Courses

The implementation model for mobile hands-on instruction that has the lowest threshold for both students and for instructors is to introduce a few simple hands-on experiments into lecture-based courses. Lecture courses normally suffer from a lack of connection to physical devices and systems, so a hands-on experience provides a different perspective to the theory and motivates students who are more practically oriented. Some of the challenges of hands-on instruction are alleviated by using only a small number of simple experiments and targeting them strategically to the most difficult concepts in the class.

The main challenges of this model are the concerns of the instructors and the logistics of the implementation. Instructors who teach theory classes are not generally as comfortable with laboratory instruction as are lab instructors and worry about procedural problems, perception issues, and time/effort. Procedural problems include equipment malfunction, problems in the laboratory steps, and trouble-shooting the experiment. A perception issue is the worry that the instructor may feel inadequate or be perceived as not knowing a topic if he/she fumbles with the experiment. Finally, instructors worry about the time needed to do hands-on activities with the worry that the coverage on other topics may be reduced as a result. They also worry that it will take a lot of their own time to develop a module or learn a module that someone else has developed. Logistical challenges include building enough of the experimental platforms that students can do the experiment in small groups during class, storing and bringing the experiment to class or handling check-out procedures for students who do the experiment at home, and organizing staff or TA help during the experiment.

This model was tried as part of an NSF CCLI grant at a large ECE program across 15 different courses, 37 instructors, and 2700 students[1-3]. The corresponding experiments include ones on circuits, signals and systems, electromagnetic, and controls. Experience gained during this grant period helped to develop implementation strategies and best practices to address the faculty concerns and logistics challenges[4]. To be successful, the model requires an established set of experimental modules using common platforms, laboratory staff support, teaching assistant support, a sufficient number of experimental set-ups for each experiment, and a faculty champion or facilitator for the experiments.

The costs and benefits of this model are discussed in Auerbach and Ferri[5] and summarized here. The costs include items for which a monetary value can be assigned such as the cost of materials and supplies for the experiments and personnel costs for TA and lab staff time. Other costs are harder to assign a value; these include instructor time and effort to prepare for the experiment (running the experiment him or herself and determining when to insert it into his/her schedule), loss of lecture time that might be devoted to other topics,

A working list of guidelines for developing in-class experiments:

- Select two or three topics from the class that are very difficult to understand based on lecture alone, and make associated in-class labs. Replace some of the examples or problems done in class on these topics with the hands-on activity. Using only one lab in a course does introduce students to the experimental process in that subject area, but there is an overhead as students must learn the experimental platform. Students feel more comfortable with a second lab and can concentrate more on the concepts than on the platform.
- Test all of the experimental modules with TAs and undergraduates who have recently taken the course. Streamline the lab procedures so that they can be finished in 30 minutes, thus allowing for students who are slow or who want more exploration time as well as unforeseen instrumentation problems.
- Ask exam questions on the concepts demonstrated in the labs, and add some minor (low-point value) exam questions on the associated experimental procedures or equipment to encourage students to understand the experimental process.
- Limit the number of TA checkpoints in the labs to a level that can be completed by the available number of TAs during the allotted class period.
- Add instructions in the lab for students to switch roles during the lab to ensure that they all receive the same experiences (rather than one student always taking measurements and the other always recording data).

A working list of guidelines for implementing in-class experiments[6]:

- Ensure adequate time in class for both instruction and implementation phases. The experiment should not be seen as an add-on, to be hurried through. Instructions may be pretaped and posted online for students to view before class.
- Emphasize repeatedly to all students to come prepared for the lab (or risk not completing it). Preparation includes completing prelab assignments, reading the fundamental concepts tutorial, printing the lab instructions for class, and viewing the instructional video.
- Have a ratio of at least one facilitator (instructor, TA, or lab assistant) in class per 10 groups. A more ideal ratio is one to five.
- Provide a fall-back for students who do not complete the lab during class. Allow them to complete the lab during TA office hours or open lab hours. This fall-back removes the panic that some students feel while trying to complete the lab during the 50 minute period.
- Assign course credit to the lab to motivate students to come to class and to participate fully in the lab.

The three expected student outcomes for in-class labs for lecture-based courses are specified below:

1. Student achievement on tests/homework/assignments will benefit from the hands-on instructional approach.
2. Students will be more positive about the course and/or course material as active learners using the modules as well as show more interest in the topic area.
3. Students will benefit from the hands-on approach in subsequent courses in terms of performance and interests.

Assessment to measure the three outcomes includes student test performance on exams and on concept inventory tests, pre-and post-experiment surveys, and a follow-on survey taken one semester later. Since this model only targets some concepts in the class, a control groups is the set of concepts that were not related to the in-class activities. A sample of the final exam data taken from one class where only one in-class experiment was used in shown in Figure 1[3]. The exam consisted of questions on basic concepts, all of which were written to be of equal difficulty. One of the questions was on the concept demonstrated by the in-class lab. Figure 1 is a scatter plot of student scores on that question versus the other questions on the exam, with the solid line shown to indicate equal performance on the two types of questions. Most of the students in the class are above the solid line indicating that they performed better on the concept question related to the experiment than questions on other topics. Another class had three hands-on activities (two in-class experiments and one take-home project). For this class, a concepts inventory pre- and post-test were taken as well as student surveys of their self-perceived understanding level for concepts. One of the surveys was taken one semester later to determine the retention of knowledge. Results for this class show significant performance improvement on concepts related to the experiments versus other concepts in the class, including persistence of the differential knowledge one semester later[2].

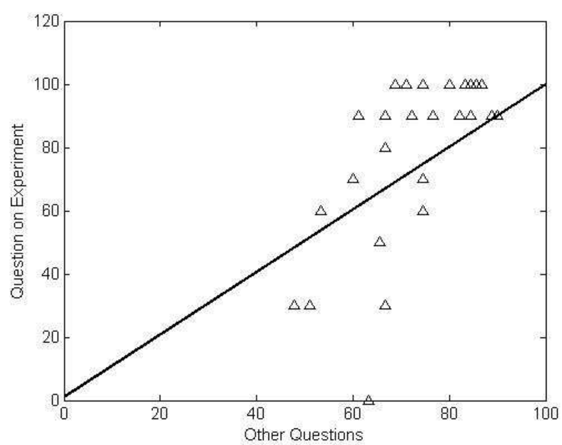

Figure 1: Final exam performance comparison of questions on fundamental concepts related to in-class experiments versus questions on concepts not covered by experiments[3].

Since the experiments were done in multiple classes by multiple instructors, the worst case scenarios was found to be where the instructors did not place emphasis on the pre-class preparation for the hands-on activities (a pre-lab and viewing a short video on the experimental platform), did not do the lab themselves, and did not give the activity any weight in the course grade. In these cases, students had little preparation for the experiment, little technical help from the instructor, and little motivation for completing the lab. Despite the disadvantages in the worst case scenario, student performance and student attitudes on the concepts related to the hands-on activities was no worse than other topics covered in the class. The benefit, that was not measured in those studies, was the skills gained by exposure the experimental methods in the subject area. Thus, even in the worst case scenario, students gained good experience without sacrificing conceptual knowledge. In the best cases, where the guidelines for implementing the labs was followed by the course instructor, student performance and student attitudes significantly improved when using the hands-on activities even one time in the semester.

2.2. Student-Owned Equipment in Lab Courses

A second model for hands-on instruction is to offer 'traditional' lab courses that are not taught in on-campus laboratory classrooms[7]. The students own their breadboards and measurement equipment, which includes a digital multimeter and a USB-powered oscilloscope. Typically, the department provides the components needed for each of the experiments as well as extra components to replace devices that may be damaged, to allow flexibility in circuit designs, and to support independent exploration of concepts. In addition, students will use a circuit simulation software package such as OrCAD PSpice and a computational software program such as MATLAB. The students perform the experiments in any location that they chose – in their dorm rooms or apartments, study lounges on campus, empty classrooms (Figure 2), on-campus cafeterias, off-campus coffee shops, or anywhere else that has sufficient space for the breadboard and a laptop computer.

Figure 2: Student working on hands-on activity in an open classroom.

The design of the laboratory experiments are structured so that no more than two new simulation and/or experimental techniques are presented in each experimental procedure, though most build upon techniques introduced in prior experiments. Students are exposed to several important techniques multiple times during the semester to reinforce learning and to demonstrate various ways in which the techniques are applied. The procedure for each experiment is written to follow Gagne's instructional events[8] such that each event is presented to the students in a consistent and systematic manner. A template based upon these events has been developed and is completed during the design of the experiment so that each event is presented to the students in a systematic manner. The template, which becomes the experimental procedure, has the following sections.

- Learning Objectives: The expected knowledge that the students will gain from the experiment including a deeper understanding of one-to-two concepts explored in the experiment.
- Preparation: The sections of the textbook in which the concepts are discussed are identified.
- Background: A brief explanation of the theory is presented along with a short discussion of the practical applications of the theory in day-to-day life, products used commonly by students, and/or in areas of research that undergraduate students would be aware of. In addition, the experimental set-up is explained. Schematics of the circuits and images of students performing specific measurements are included. Ties between the current experiment with experiments performed previously are also made.

- References: Books other than the course textbook, technical papers, and websites are provided so that interested students can read further on the topics covered in the Background section.
- Materials: The components required to perform the experiment are listed.
- Experimental Procedure: A step-by-step set of instructions are provided in the following order – (1) Analysis, which are hand calculations and MatLAB programs that are expected to be done before the student start the hands-on section of the experiment, (2) Modeling, which are any simulations that the students are expected to perform using software packages, (3) Measurements, which cover the set of instructions on how the components should be assembled and what measurements are to be made as well as questions interspersed in the instructions that are intended to guide the students as they analyze the results of the measurements and to spur them to consider why differences may exists when the students compare the results from the measurements with those obtained from the steps performed in the Analysis and Modeling.

The goals for these lab courses are similar to those that underpin the other models for hands-on learning[7] and have comparable learning outcomes to those of the classroom-based lab courses. However, the expectations of students are different as they are required to carry out the experimental procedures with limited face-to-face instructional support. The instructional support for these lab courses is provided via two venues depending on whether the course is taught during the academic year or online during the summer. During the academic year, there is a dedicated classroom called the Open Electronics Laboratory (OpEL) where graduate TAs have regularly scheduled hours to answer questions. During the summer, the online students Skype the graduate TA to obtain real-time instructional support[9]. A Flash presentation on each experiment has been developed, which a brief overview of the objectives of the experiment, description of the capabilities of the measurement equipment, introduction to information contained in component datasheets, and helpful hints on circuit design and construction. Approximately fifty Flash tutorials are available that describe how to perform particular measurement techniques, how to program in MATLAB, and how to run specific PSpice simulations, and to address commonly asked questions. The Flash presentations and tutorials are grouped in modules for each experiment on the course site in Scholar, which is the Virginia Tech implementation of Sakai platform. Video demonstrations are also available as hotlinks in the report templates that are provided to the students[10-11].

In order to obtain credit for each experiment, students must demonstrate a subset of measurements that are mentioned in the lab procedure to the TA. Given the emphasis on learning objectives associated with experimental practices, students are provided with report templates to document the results of their analysis, simulations, and measurements and to detail their conclusions on the causes of the differences between expected and measured parameters.

There are several factors why this approach was adopted approximately 10 years ago at Virginia Tech. First, there was insufficient laboratory classroom space for the estimated 14 sections of lab classes per semester that would have to be taught if classroom-based circuits labs were introduced into the ECE curricula and, later, the 9-17 extra sections of circuits lab classes (depending on the semester) when labs were also introduced into the circuits course taken by students in the BSME program[12]. Secondly, budgetary constraints meant that the resources were not available to increase the number of graduate teaching assistants and laboratory staff or to purchase lab equipment required to teach the additional classroom-based lab courses. The stand-alone laboratory courses, as opposed to integrating hands-on learning modules into existing lecture courses, allow the students who transferred from schools within the Virginia Community College System to continue to receive credit for the lecture courses, but have to to take the companion laboratory course at Virginia Tech if their institution did not offer a suitable lab course. This allows the existing articulation agreements to remain unchanged. Another consideration is that there were few classrooms that had a sufficient number of electrical outlets at the time when the hands-on experiments were adopted into the curriculum, which presented significant complications to the scheduling of courses if the hands-on activities were conducted during the class session. Lastly, the instructors assigned to teach the lecture courses change every semester and include adjunct professors, faculty members from other departments, and graduate students who have completed their Masters degrees. The effort to continually instruct the instructors on techniques to incorporate the hands-on learning modules into their lectures each semester is not sustainable.

To insure that the desired student learning outcomes from the hands-on activities are obtained each semester, a single faculty member was given responsibility to oversee the new circuits laboratory courses for ECE students. Recently, this responsibility was transferred to a member of the department’s lab staff. A second member of the lab staff is responsible for the hands-on laboratory course for ME students. A total of eight graduate teaching assistants per semester during the academic year provide technical assistance on the four nontraditional lab courses that are currently taught at Virginia Tech. One additional graduate student is employed during the summer semester to support the online lab course.

The response by the faculty to these courses has been very positive. Several of the other engineering departments have made multiple requests that the ECE department offer a similar circuits laboratory experience for their students. However, limitations on resources within the ECE department have prevented the expansion. Assessment of the two circuits laboratory courses taken by the electrical and computer engineering undergraduates has been conducted for the past two years. Students are invited to participate in two online assessment surveys; one survey is conducted in the first week or two of the semester and the second survey is conducted upon the completion of the final experiment of the semester. Students are given extra credit towards their final grade in the course when they have completed one or both of the surveys, even if they elect to have their data excluded from the study. The initial analysis of the results has shown that the two courses have achieved the goals of motivating students’ interest in the field, supporting learning of the concepts presented in the companion lecture courses, and increasing students’ self-confidence to design, simulate, construct, and characterize circuits[13]. A longitudinal study of the impact of the hands-on laboratory courses is planned.

2.3 Mobile Studios

A Mobile Studio is technology-based pedagogy based on inexpensive hardware/software which, when connected to a PC (via USB), provides functionality similar to that of electronic laboratory equipment (scope, function generator, power supplies, DMM, etc.) typically associated with an instrumented studio classroom. The Mobile Studio IOBoard (Figs. 3 and 4) is a small, inexpensive hardware platform for use in a home, classroom or remote environment. When coupled with the Mobile Studio Desktop software, the system duplicates a large amount of the hardware often used to teach Electrical Engineering, Computer Engineering, Physics and K-12 technology-related courses; in addition to a myriad of industrial and commercial utilizations.

In the 1990s, Rensselaer embarked on a large scale effort to develop and implement a new pedagogical model called Studio. Studio Pedagogy[14] was originally developed for 1st and 2nd year science and math courses[15] and then used in essentially all of the core ECE courses. A typical Studio class meeting begins with a short lecture, demo or hands-on activity to introduce the key topic or topics of the day. The introduction is followed by paper and pencil calculations, simulation, and/or experiments, with breaks for discussions and additional lectures as needed. Lectures could be any length from a few minutes to over an hour, with most around 20 minutes. The majority of all class time is dedicated to student-focused activities with instructors and other course staff generally working as a 'guide on the side' rather than a 'sage on the stage,' which was an expression heard constantly at the time. Studio was found to be a very good way to deliver engineering education and attracted a steady stream of visitors to the new classrooms built specifically for this purpose. Nearly all visitors went away hoping they could implement something similar. However, very few were successful because the costs were so high. The facilities necessary to provide lectures, paper and pencil problem solving, numerical simulation and traditional experiments all in the same room cost about $10k per seat. The investment in these remarkable rooms required elaborate security systems and placed a hard limit on the number of students that could be accommodated in an individual section. The learning and teaching environment was amazing, but implementation logistics were problematic.

At the end of the 1990s, Don Millard and his colleagues developed a vision for a new, inexpensive studio for teaching electronics based on replacing the very expensive standard set of instruments found on a typical lab[16]. When no commercially available product was found, he led an effort to design and build a small board that could duplicate the needed functionality. With the help of Analog Devices and ADI Fellow Doug Mercer, RPI student Jason Coutermarsh, funding from NSF and Hewlett-Packard, and the help and support of a growing, but small number of true believers from RPI, Howard, and Rose-Hulman, he went through several designs, with varying degrees of success, until what is called the RED2 board became generally available in 2008. Earlier designs (including RED and BLUE) showed that the educational vision could be realized, but were, as a colleague at Rose-Hulman has said, not quite ready for prime time. The RED2 board had all the necessary functionality required and the robust design to survive regular usage by undergrads. The cost of each was about the same as a textbook or about $150.

The RED2 board has two analog input channels (i.e. scope or DMM inputs), two arbitrary waveform outputs (i.e. function generator outputs) and D.C. voltages supplies (±4V. The hardware package also incorporates 16 digital I/O channels, 2 PWM outputs, digital GND and analog outputs to drive earphones or speakers so both analog and digital electronics can be addressed. The Mobile Studio Desktop software provides access to scope, function generator, spectrum analyzer, arbitrary waveform generator, analog input (i.e. DMM), and audio output functionalities. The hardware can also work with programs written in a very wide variety of languages such as LabView, Matlab, C, C#, and Python. For example, an extensive set of LabView executables come with the Desktop package when it is downloaded. Sample programs written in other languages are available from the Mobile Studio Project website, including a data logger program written in C# that samples analog signals every minute or so for an almost indefinite amount of time[17].

The Mobile Studio was first used in the same ECE course in which Studio Pedagogy was introduced – Electric Circuits. This 2nd year course is the first serious introduction to analog circuits in the Electrical Engineering and Computer and Systems Engineering curricula. The original implementation of Mobile Studio addressed only the existing studio activities, but without requiring the expensive classroom used previously. This made possible larger enrollments because any room in which the students had access to power for their laptops became a studio classroom. All of the characteristics of Studio pedagogy were incorporated. Topic introduction with a short lecture, demo or hands-on activity was followed by paper and pencil calculations, simulation, and/or experiments, with breaks for discussions and additional lectures as needed. Lectures could be any length from a few minutes to over an hour, with most around 20 minutes.

Mobile Studio pedagogy was then moved to the electronics course taken by non-majors: Electronic Instrumentation. Again, the original focus was on replacing expensive equipment with the student-owned Mobile Studio kit which also allowed for larger sections. For both courses, the hardware used was the first RED board, which was limited to audio frequencies and required assistance from good support staff to keep things working for students. Figure 3 shows the experimental setup using the RED board to characterize the motion of a cantilever beam. Note the decaying sinusoid on the laptop screen and the small toolbox which holds everything needed to do the measurement, except for the beam. Mobile Studio was also tested and implemented at Howard and Rose-Hulman. A team from the Evaluation Consortium at U Albany provided assessment, which included pre and post surveys on background and attitudes, classroom observation and student and faculty interviews[18-20].

For a variety of reasons, there were three general models utilized for Mobile Studio course delivery. In the full implementation model, each student (e.g. in Electric Circuits) or each team of two (e.g. in Electronic Instrumentation), purchases a kit consisting of a Mobile Studio board, some simple tools (screwdriver, wire stripper, needle nose pliers), protoboards, circuit components and a storage box. Occasionally, other items (e.g. DMM) are included. The total cost of the kit has varied from $125-$175, depending on the cost of components and tools. The student-owned kits are not stored in the classroom; students are completely responsible for them. Damaged hardware, which only very rarely occurs, is handled by temporarily swapping boards while a technician makes repairs. Typically, only two or three boards per term (out of 60) require any work. A second fully Mobile Studio model is realized by loaning kits (with or without a fee of some kind) to students for the term, which makes possible the same pedagogy, but adds costs to department or school budgets. When students purchase their own kits, they then own a fully functional portable lab that can be used anywhere or anytime, and all coursework is based on the latest versions of both hardware and software. A third model, in which the kits remain in the classroom and are shared by all students, is only mobile in that class meetings can be moved to any room in which there is power available for student or department owned computers. It is this last model that has been popular at institutions with very limited budgets (e.g. universities in Sub-Saharan Africa, high schools, community colleges), because fully functional, hands-on classes can be realized with a much smaller investment than for standard instruments. All three models also make it possible to add mini-lab experiences to almost any class without requiring a special purpose classroom. Experiments can be so small that they can be done on any reasonable sized desk. Staffing requirements vary with class size. It is, in fact, possible to carry a Mobile Studio for two dozen students in a carry-on suitcase, which makes it ideal for recruiting and other outreach events. Sections with enrollments greater than 50 may have 2-3 TAs in addition to an instructor. The availability of online learning materials also reduces staffing requirements. In essentially all cases to date, there has been a highly qualified technician available for occasional repairs.

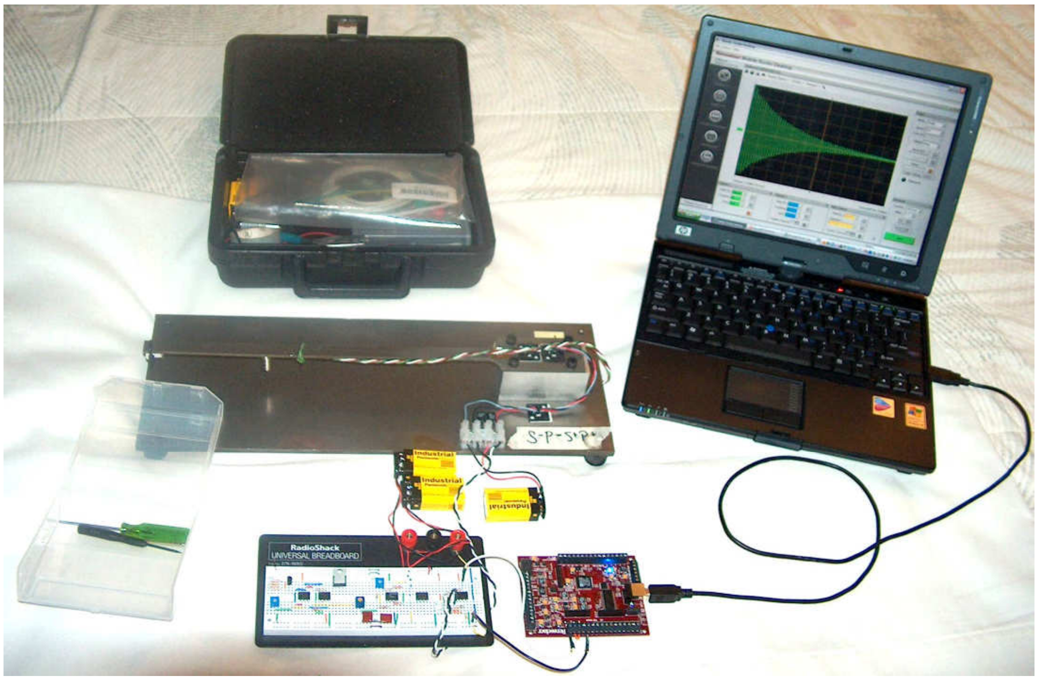

Figure 3: Cantilever Beam Experiment with RED Board

With the introduction of the more capable and reliable RED2 board, Mobile Studio pedagogy expanded to new universities (e.g. BU, Morgan State, Wisconsin, and other four and two year institutions in the US and abroad) and to additional courses (e.g. Electronics at RPI and courses for non-majors at Rose-Hulman). The use of a RED2 board at a workshop in Ghana is shown in Figure 4. In addition to making possible the use of hands-on activities at universities with very limited operating budgets, such as those found in Sub-Saharan Africa, the most exciting changes were to the pedagogical model itself. Rather than just providing a much lower cost approach to studio instruction, entirely new ideas could be implemented that were never possible using standard classroom tools. These were based on the key difference between mobile learning platforms like Mobile Studio and the Digilent Analog Discovery – that they can be used by students anywhere and anytime. Thus, students were given hardware homework because they carried their lab in their backpacks. They worked through the assigned tasks and then demonstrated their results when they were next in class, in a manner similar to the Virginia Tech Lab-in-a-Box. Flipped classrooms were also implemented, most notably in Electronic Instrumentation, where students can watch video lectures and try ideas out experimentally as they are learning the course material. There are many, many more ideas to be explored that are now possible with this new approach to instruction[17,21-23].

Figure 4: RED2 board at a workshop in Ghana.

Pre-surveys were administered to students in the first week of the course; post-surveys were completed the last week of each course. Observations were conducted throughout the semester; and interviews were conducted via telephone or in person at the end of the semester. Specific variables and constructs examined included modalities and frequency of use, confounding variables of instructor experience, student experience and background knowledge in electrical engineering, support and resources, and student access to the Mobile Studio hardware as well as indicators of learning and preparation for learning. This external validation of use and outcomes found Mobile Studio Pedagogy: ***(1)*** Met sound educational practices; ***(2)*** Was easy to integrate into the curriculum; ***(3)*** Facilitated retention and transfer of knowledge; and ***(4)*** Met national technology standards. The platform had multiple instructional uses, which met diverse student needs. It enabled hands-on practice of course content and was effective in stimulating reflection on course content[18,20]. The multi-stage scaffolding of fundamental concepts using paper/pencil, in-class hardware problem analysis, and an out-of-class project was very beneficial. In-class activities and take-home experiments were designed, developed, utilized, and evaluated.

3.0 Summary of Assessment Tools Used

Surveys and test performance are the main assessment methods for these studies. One type of control group used are classes taught in a traditional setting, that is, did not have hands-on activities. More recently, since all classes have been reverting to using hands-on activities at the universities hosting these projects, another type of control group has been utilized: the set of concepts that are not related to the hands-on activities.

Pre and post student surveys: The goal of these surveys is to determine student preferences on teaching styles and to determine students' self-perceived competence on topics covered in the class. Student preferences on teaching style are determined by asking students to rate the following methods: lecture, instructors working problems in class, students working problems in class, instructor-led demos, hands-on demos, hands-on experiments). Students self-perceived competence is measured by asking students to rate their understanding of different concepts covered in the course).

Survey taken one term later: The goal of the survey taken one semester after the end of the term in which the hands-on activities were done is to determine the persistence of the effect of the hands-on activity. Students are asked to rate their competence on the concepts covered in the course and whether they took any or would take any follow-on elective courses in the subject area.

Concepts Inventories: Concepts inventory tests are taken at the beginning of the term and repeated at the end of the term. Some concepts are not related to the topics covered by the hands-on activities while others are. Relative improvement on knowledge of concepts related to the hands-on activities versus concepts that are not related to hands-on activities are compared.

Course Exams: Student performance on questions related to concepts covered by the hands-on activities versus concepts not related to the activities are compared across sections that did not have the hands-on activities.

Focus Groups: Open ended questions are asked of a small group of seniors to obtain input on courses in which the hands-on learning activities would be beneficial to student learning and on areas of improvements to overall hands-on pedagogical approach.

Senior Exit Surveys: The goal of the survey is to determine the impact of hands-on learning as students reflect on their academic experiences. Student input also reveals the expected value of these experiences in their professional careers as they have, typically, completed their job search and have an understanding of the knowledge and skill sets that will employ in the near future.

4.0 Comparison

The three models of implementation of the hands-on activities can be compared against several criteria as shown in the table below. The model described in Section 2.1, Small In-Class Activities in Lecture-Based Courses, is abbreviated as “Small In-Class Labs.” The model described in Section 2.2, Student-Owned Equipment in Lab Courses, is abbreviated as “Ubiquitous Lab Classes.” And the third model described in Section 2.3 Mobile Studios does not need further abbreviation in the table.

Benefits	**Small In-Class Labs**	**Ubiquitous Lab Classes**	**Mobile Studios**
Level of integration across material within a non-lab course [1]	Low	NA	High
Level of integration across courses in a curriculum [2]	High	Medium	High

Achieving learning objectives focused on fundamental theoretical concepts [3]	High	Medium	High
Achieving learning objectives focused on experimental methods [4]	Low	High	High

Explanatory Notes:

[1] This is a key difference between the studio model and the in-class model.

[2] The Small In-Class Labs model is a curriculum-centric model where it introduces a few experiments per course but then reuses the same board in several different courses. The Mobile Studios model is introduced in three courses in science and engineering and then used in follow-on courses. The Ubiquitous Lab model is similarly centered on laboratory-style courses. Both of these two models can be reproduced across all similar courses in a curriculum.

[3] The Small In-Class Labs model is meant to be an easy first step in a school's adoption of hands-on by gaining wide impact (across many courses and instructors) with very little change to the existing instructional methods, facilities, or course content. As such it has high impact on a few theoretical concepts (ideally, the most abstract in the course), whereas the Mobile Studios model has a much larger impact on all concepts in the course but requires a larger deviation from standard teaching styles.

[4] Both the Ubiquitous Labs and the Mobile Studio models emphasize laboratory methods, including trouble-shooting skills. The experiments mirror those found in regular centralized labs, but done with mobile platforms. The Small In-Class Labs are streamlined to be done in class, or perhaps as take-home projects, so that the emphasis is a demonstration of theoretical concepts rather than experimental procedures.

Costs	**Small In-Class Labs**	**Ubiquitous Lab Classes**	**Mobile Studios**
Learning curve for students [5]	Low	Low	Medium
Learning curve for new faculty (represents how easy this model can be adopted by new faculty and other schools) [6]	Low	Low	Medium
Material costs to students [7]	Low	Low	Low
Material costs to school [8]	Low	Low	Low
Personnel costs: staff and TAs [9]	Medium	Medium	Medium
Facility costs [10]	Low	Low	Low

Explanatory Notes:

[5] How easy is it for students to use any of the modules without assistance from an instructor or TA? All self-contained modules can be made easier for students with sufficient guidelines and trouble-shooting help. The equipment in the mobile studio model falls under the same category of having a low learning curve; however, the nature of the studio model of instruction requires that the students put effort into discovering concepts and learning from failures.

[6] Similar to item [5], the learning curve for faculty is based on the level of self-containment of the modules. The Small In-Class Lab model is rated as having a low learning curve since the modules are built for instructors who primarily teach lecture courses and are not very familiar with laboratory instruction. The Ubiquitous Lab Class model would be reasonably easy for any instructor who is already familiar with laboratory instruction. The hands-on activities in the Mobile Studio model are relatively easy to learn; the larger difficulty would be in teaching faculty how to instruct in a studio environment.

[7] The costs of the kits (board plus parts) range from $125 to $225 for all the cases, which is comparable to textbook prices. In some cases, supplemental textbooks are available for free online, such as one available by Digilent [Dig].

[8] In cases where students purchase an electronics parts kit, the material costs to universities is minimal. In cases where the experimental platform requires more than basic electronics, such as a motor control experiment, the platform can be purchased by the university. Since so many students must use these experiments at once, the costs should be less than $50 per unit. Ideally, these units might be used in multiple courses. For example, a guitar string experiment [Fer5] costs less than $25 per unit and can be used for signals and systems courses as well as vibrations courses.

[9] Compared to regular lecture classes, the in-class labs do require more TA help and more lab support. However, since only 2-3 labs are done per class per term, the additional support is minor since regular course graders can provide the in-class support on the days of the labs. The Mobile Studio model has many more hands-on experiments than does a regularly scheduled lecture course and would require dedicated labs staff and/or TA support to facilitate the classes. Compared to a regularly scheduled lab classes, the TA support and lab staff support for the Ubiquitous Lab Class model is much smaller since TAs only need to be present when students need to demonstrate their labs and to be able to answer questions not answered by the self-help trouble-shooting guides.

[10] No additional facilities are needed for any of these models since the hands-on activities are either done in regular classrooms or by students on their own. In the case of the Ubiquitous Lab Class model, there is needed space for lab demos and TA office hours; however, this space is dramatically reduced from that of regularly scheduled labs in centralized lab facilities.

4.0 Summary

The three models of hands-on education use different strategies and take different levels of commitment from universities and from instructors. The first one, in-class experiments on a small-scale level, aims at targeted intervention and has the lowest threshold for instructors, students, and administrations. The mobile studios model has the highest threshold but may have the largest impact by fully integrating classes with hands-on activities. The model where regular, full-scale labs are done by students using student-owned equipment can serve to replace the centralized laboratory model, which is costly to universities, with a mobile version where students have more time to explore the lab activities.

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