Physics Education Research:
A Model for Introductory Laboratory Reform

Teresa L. Larkin¹ and Mark Mathis²

Abstract - During the 2002 – 2003 academic years a decision was made at American University to reform the introductory General Education science classes by increasing the number of credit hours from 3 to 4. The intent of this reform effort was to add more substance to the introductory courses by increasing the laboratory experiences offered, and to make them comparable in credit hours to most introductory science courses around the country. As a result of this reform effort, the introductory physics classes were required to double the number of laboratory activities performed by the students during a given semester. The main objective behind increasing the number of laboratory activities was to increase the hands-on experiences of the students for the various topics covered within the curriculum. Through an internal grant award from American University, a significant amount of new laboratory equipment was purchased in spring 2003 and a number of new laboratory activities were created during the summer of 2003. The design and development of the new laboratory activities will be described as they relate to current research in physics education. The research in this field has clearly shown that student learning can be enhanced through the use of content-specific, interactive engagement (IE) strategies. Tips regarding the choice of equipment for the introductory physics laboratory will also be shared. In addition, the overall reform effort within the introductory physics classes and laboratories will be presented through a discussion of effective pedagogical strategies. The new laboratory activities were successfully piloted with over 100 students during the fall 2003 semester. This paper will highlight student and instructor experiences with the new activities during the pilot semester. A description of the newly-created laboratory activities through the lens of current research in physics education should provide faculty teaching laboratory-based, introductory physics or engineering courses with some useful ideas and techniques for reforming or refreshing their own courses.

Index Terms – Interactive engagement strategies, laboratory design and development, physics for non-science majors, physics laboratory reform.

INTRODUCTION

The primary purpose of teaching is to facilitate student learning. Traditional teaching methodologies have been shown to put students in a role of passive rather than active learning [1]. In addition, traditional instructional methods have also been shown to be very inadequate in terms of the promotion of deep learning and long-term retention of important concepts. Students in traditional classrooms acquire most of their "knowledge" through classroom lectures and textbook reading. A troubling fact is, after instruction, students often emerge from our classes with serious misconceptions [2] – [7].

A significant body of educational research supports the fact that students must be functionally active to learn [8] – [10]. Furthermore, Koballa, Kemp, and Evans [11] note that "ALL students must become scientifically literate if they are to function in tomorrow's society" (p. 27). Scientific literacy is of critical importance for all students, at all educational levels, but is especially important for students who are not science or engineering majors. In written remarks regarding the improvement of science and technology literacy of all undergraduate students, given to the National Science Foundation and contributed as part of the Education and Human Resources Advisory Committee Public Hearings on Undergraduate SME&T Education [12], it was suggested that:

"In the information age we have already, no college educated person can expect to be fully equipped for a job or career without at least a working knowledge of modern scientific theory and a modicum of technical competence and know how. This will require our colleges and universities to revisit the general curriculum and revise the requirements to ensure that their students are prepared. This will not happen without the enlightened leadership of scientists and other academics. It will not work if all the scientific community is willing to offer is the usual array of introductory courses intended to introduce the student to the major. True literacy of all students will require science departments to become much more creative; to work collegially with other science departments and resource centers. Scientists must offer courses that the non-scientist likes and which are conceptually oriented, not just fact oriented. The 'sage on the stage' will have to be replaced by the talented storyteller and the multimedia expert who has not
only mastery of the material but mastery of the method of conveying the exciting and dynamic world of science” (p. 34).

The National Science Education Standards [13] further emphasize that inquiry-based techniques should form the core of what it means to learn and do science. Edwards [14] suggests that the publication of the National Science Education Standards offer reason to be optimistic that inquiry-based learning will become a central part of science education. Inquiry-based learning strategies originate from the constructivist model and encourage an active, hands-on approach to learning [15] – [16]. The constructivist approach embraces the idea that knowledge cannot be acquired passively [17]. In addition, the National Science Foundation currently has several programs that promote the integration of standards- and inquiry-based SMET educational materials and instructional strategies from elementary through graduate school [18].

Science classes, furthermore, are often seen by many students to be threatening and intimidating places to be. Tobias [19] has been critical of introductory college science courses and has argued that typical classrooms are “…competitive, selective, intimidating, and designed to winnow out all but the ‘top tier’ … there is little attempt to create a sense of ‘community’ among average students of science” (p. 9). Hence, a traditional science classroom may present potential barriers that could inhibit learning for some students. Inquiry-based active learning strategies may provide one mechanism through which these barriers to learning could be reduced and possibly even removed.

This article describes a reform effort at American University designed to enhance and enrich the laboratory experience for students enrolled in an introductory General Education physics class for non-majors. The impetus for this reform was grounded in the idea that enriching the laboratory experience to increase the amount of hands-on, interactive reform was grounded in the idea that enriching the laboratory experience every week, rather than every other week, as had been done in the past.

Overview of the General Education Program at American University

Regardless of their degree objectives, all undergraduate students at American University (AU) are required to complete the General Education Program [20]. The current program was implemented in 1989 and has since been acknowledged as an exemplary model by other institutions. The General Education program requirements consist of 31 credit hours taken from courses in 5 curricular areas. These curricular areas are shown in Table 1.

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<tr>
<th>Curricular Area</th>
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<td>Area 1</td>
<td>The Creative Arts</td>
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<td>Area 2</td>
<td>Traditions that Shape the</td>
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<td>Western World</td>
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<td>Area 4</td>
<td>Social Institutions and</td>
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<td>Behavior</td>
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<td>Area 5</td>
<td>The Natural Sciences</td>
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Within each curricular area students are offered a choice between two course clusters. Each cluster includes several foundation-level courses and a larger number of second-level courses. Students then choose two courses in each curricular area. One course must be a foundation-level course and the other a second-level course from within the same course cluster. Students thus take 6 credit hours within areas 1, 2, 3, and 4, and 7 credit hours in area 5.

Of particular interest in this paper is Area 5, The Natural Sciences. Following a recent review of the entire General Education Program, a university-wide decision was made to transform all foundation level courses in the Natural Sciences portion of the course from 3 to 4 credits. This decision was put into effect in the fall semester of 2003 and had several implications for the foundation level science courses. However, because of the equipment intensive nature of introductory physics laboratories, this decision had enormous implications for the foundation level physics course. What this decision essentially required for one of the introductory General Education physics course, Physics for the Modern World, is that students would have now have a laboratory experience every week, rather than every other week, as had been done in the past.

Before a description of the changes to the laboratory portion of the Physics for the Modern World course are described, an overall description of the course follows. In addition, a brief description of the student population that typically enrolls in the course will also be shared.

The Physics for the Modern World Course and its Student Population

Physics for the Modern World (PMW) is now a 4-credit, foundation-level course in curricular area 5 of the General Education core of courses at American University. Students who enroll in this course do so almost exclusively to satisfy their Natural Sciences requirements towards graduation. Many of these students enter the classroom with very limited backgrounds in mathematics and science. Although some students have had a course in high school physics before taking PMW, many have not.
Many traditional teaching methodologies have clearly been shown to put students in the role of passive, rather than active, learning [25]. Often times this is known as a “teaching by telling” approach [26]. From an instructor’s point of view, a relatively large amount of information can be passed along to students in a limited amount of time with this type of approach. However, an extensive amount of educational research has shown that most students find that the “teaching by telling” approach is not effective. Students cannot digest and comprehend large amounts of material that has only been passively received. Wankat suggested that content tyranny occurs when instructors allow the need to cover the content control the processes of teaching and learning in a course [27]. Traditional instructional methods have also been shown to be inadequate in terms of promoting deep learning and long term retention of important physics concepts. A learner-centered classroom and laboratory that focus on an interactive, hands-on approach to learning will oftentimes lead to a deeper understanding of key physics content.

The section that follows outlines the redesign and development of new interactive laboratory activities for the PMW course. In addition, a description of the software and hardware that were purchased to aid with the implementation of these new activities is also presented.

LABORATORY REDESIGN AND DEVELOPMENT IN PHYSICS FOR THE MODERN WORLD

Prior to fall 2003, students enrolled in PMW performed a laboratory activity every other week. Topics for which laboratory activities were available included:

- Measurement and Graphing
- The Simple Pendulum
- Standing Waves on a String
- Projectile Motion
- Conservation of Momentum
- Archimedes’ Principle

Certainly these lab activities do not even come close to covering many of the key topic areas in a typical first semester course. The first three laboratory activities did not involve the use of a computer at all. The latter three activities did make use of a computer along with a universal lab interface (ULI) used for data acquisition and the accompanying software developed by Vernier Software and Technology [28]. This software and a limited amount of other equipment was purchased in 1998 by the lead author through a previous NSF Instrumentation and Laboratory Improvement Award [29]. The purchase of equipment through this grant award was critical to the implementation of a more technology-based, learner-centered introductory physics laboratory at American University.

When the change was implemented in fall 2003 to have students have a laboratory experience every week (instead of every other week) a considerable amount of new equipment and software and hardware updates and replacements was mandated. In the sub-section that follows a description of how the introductory physics laboratory was completely redesigned and transformed over the course of a single summer is shared.

Laboratory Redesign: Spring & Summer 2003

During the 2001 – 2002 academic years, the General Education Program at American University underwent an extensive 10 year review. A committee consisting of students and faculty from each college was charged with the task of making recommendations for changes and enhancements to the program. In early spring 2003, an announcement was made that the recommendations had been approved and would be implemented beginning in fall 2003. Once this announcement was made, the lead author experienced several moments of shear terror! A large number of questions immediately surfaced such as: Where was all the new equipment going to come from to enable the department to essentially double the number of introductory level laboratories? Where was the money going to come from to purchase the much needed equipment? How could the required number of new laboratory activities possibly get designed and implemented prior to the looming deadline of fall 2003? Who was going to make all of this happen?

In March 2003 the lead author prepared an internal grant request and submitted it to the Dean of the College of Arts and Sciences and to the Director of the General Education Program. In that proposal she outlined the current state of the introductory physics laboratories and the need to purchase new and updated equipment for the laboratories. American University is deeply committed to having the best learning models and experiences for its students. Furthermore, the university has a long-standing tradition of supporting courses within the General Education Program. Because of this commitment to quality education, the college and university fully funded the grant request. The funding provided approximately $40,000 in new equipment along with summer support for the authors.

Once the funding had been secured, the lead author was put to the task of determining what equipment would be needed in order to maximize the use of existing equipment and what software and hardware updates and replacements would be needed. There was no time to waste in making these decisions. Numerous faculty members at other institutions who are also making using of a research-based, interactive, hands-on approach to introductory physics were consulted as to what they would recommend in terms of learning tools for the laboratory.

After careful consideration, a decision was made to equip the laboratory with PASCO scientific USB SW750 computer interface boxes, the DataStudio™ software, and a sizeable amount of new equipment [30]. A complete list of all
equipment purchased can be obtained directly from the lead author and will not be included here. Once the new hardware and software had arrived, the authors were then challenged to learn how to make it all work in a very short period of time.

Beginning in May 2003 the authors embarked on a journey to gain expertise in using the new equipment. In addition, six new laboratory activities had to be created, designed, and developed over the next few months. A key goal of the lead author was to completely rewrite the introductory physics laboratory manual that the students would use in the fall 2003 semester.

The SW750 interface box and DataStudio™ software can be used with photogates and various sensors (such as force and motion sensors) to collect, record, and graph specific data as needed for a given activity. The DataStudio™ software is quite user-friendly. During the summer months a total of seven new laboratories were created on the following topics:

- Introduction to DataStudio & 1-Dimensional Motion
- Newton’s 2nd Law & Friction
- Impulse & Newton’s 3rd Law
- Conservation of Energy
- The Work-Energy Theorem
- Conditions of Equilibrium
- Centripetal Force

In addition, the Projectile Motion, Conservation of Momentum, and Archimedes’ Principle laboratory activities were enhanced to include the use of the new hardware and software. Because of space limitations, details will not be provided on every new activity created. Rather, in the following section an overview of the Introduction to DataStudio & 1-Dimensional Motion activity will be provided. All activities have been published in the revised Physics for the Modern World Laboratory Manual [31]. In addition to the publication of a new laboratory manual, the author also created a laboratory set-up guide complete with photographs of all equipment needed for a particular laboratory setup as well as a detailed table documenting where every piece of equipment was located.

**OVERVIEW OF ONE NEW LABORATORY ACTIVITY**

One of the new activities created was called Introduction to DataStudio & 1-Dimensional Motion. The main goal of this three-part activity was to introduce students to the hardware and software and give them an opportunity to learn to use the interface box along with a force sensor, a motion sensor, and a photogate, as well as enhance their understanding of 1-dimensional motion. These items are illustrated in Figure 1.

In the first part of the activity the students used a force sensor to measure the tension in a string when a stationary mass was hanging from it. The students could then compare the measured tension to the known weight of the mass.

In the second part of the activity, the students learned to use a motion sensor to create plots of their own position-, velocity-, and acceleration-versus time. To make this part of the activity more interesting, students were presented with some preloaded position- and velocity-versus time graphs and they were asked to try to match their own motion with that on the graphs. In addition, students created a digits display box in which they would get a “Match Score” between the shape of the preloaded graph and the one that they generated by walking back and forth in front of the motion sensor. The lower the match score, the closer the preloaded and student-generated graphs were to being identical. The students enjoyed this and contests were set up during the week between each of the lab sections to see which team of students could generate the lowest match scores.

In the final part of the activity students used a photogate to measure the speed of a falling ball that had been dropped from various heights. Students could easily see that as the dropped the ball from greater and greater heights, the velocity of the ball as it passed through the photogate would increase. This activity supported what the students were learning in class about the topics of free fall and one-dimensional motion. The following section provides a brief overview of the fall 2003 pilot semester in which the new laboratory manual and activities were unveiled. A brief summary of student and instructor experiences during this pilot semester will also be highlighted.

**PILOT SEMESTER: FALL 2003**

Approximately 102 students were enrolled in PMW in the fall 2003 semester. A total of 8 sections of laboratory were scheduled to accommodate this number of students.

Students began the semester by performing the Introduction to DataStudio & 1-Dimensional Motion activity as this was designed to familiarize them with the hardware, software, and various sensors they would be using throughout the semester. While minor errors were discovered in the laboratory manual, overall, this activity was performed successfully by all of the students.

With each new laboratory activity performed, minor errors and glitches in the laboratory manual were discovered. Given the short time frame in which the laboratory manual was written, this was naturally to be expected.
One observation that was made was that the level of rigor now present in the laboratory activities was much higher than in the past. In fact, the instructor for the calculus-based physics laboratories even made use of some of the new laboratory activities in her lab sections. The hope is that the new activities will be adapted more broadly for use in both the calculus- as well as the trigonometry-based physics classes at American University.

Because of the added rigor and sophistication of the new laboratory activities, some of the instructors found that a reasonably small number of students had difficulty completing the laboratory activities in the allotted time. Part of the reason for the difficulty in completing the labs on time had to do with the fact that the activities were new to the instructors as well. A certain learning curve is naturally present when anyone has to gain expertise with so much new hardware and software in a short period of time.

Overall, the pilot semester was very successful in terms of providing students an opportunity to have hands-on experiences with so many more topics present within the introductory physics curriculum. The additional laboratory activities certainly served to enhance the opportunities students had to become actively engaged with the physics content they were studying in class.

**CONCLUSIONS AND FUTURE IMPLICATIONS**

Research in physics education has clearly shown that the use of hands-on, interactive engagement, active learning strategies in introductory courses can lead to longer term understanding and retention of key physics content. It is imperative, especially in a course for non-majors, that students be given an opportunity to interact on a personal level with the content being studied. The laboratory component of any introductory course is therefore a crucial element in terms of providing students an additional and important venue through which to learn physics.

While the laboratory component of an introductory course is known to be an essential part of the student learning process, it is often simply taken for granted. The laboratory component, however, is often a critical learning tool for many students, particularly those whose learning styles involve hands-on, interactive engagement, active learning strategies. Research in physics education has clearly shown that the use of hands-on, interactive engagement, active learning strategies in introductory courses can lead to longer term understanding and retention of key physics content. It is imperative, especially in a course for non-majors, that students be given an opportunity to interact on a personal level with the content being studied. The laboratory component of any introductory course is therefore a crucial element in terms of providing students an additional and important venue through which to learn physics.

Very little attention is paid in the research and educational literature to the need to provide students with this viable learning tool. In fact, often times there is a serious disconnect between the lecture and laboratory portions of the traditional introductory course. Moreover, introductory physics is being taught without a tangible laboratory component at many institutions around the country. It is the contention of the authors that if the laboratory portion of the introductory physics course is carefully thought out and pedagogically imbedded within the overall curriculum of the course, that students will have the maximum opportunity to learn physics.

### REFERENCES


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