Online Introductory Physics Labs: Status and Methods

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Abstract

Nearly 400 US colleges and universities offering undergraduate introductory physics courses were surveyed to determine the extent to which introductory physics instruction is currently available in a fully online format. A second survey, targeting those institutions offering online introductory physics courses, identified current approaches to and plans for making the corresponding physics laboratory course components available online. A single approach towards online laboratories was selected, and a set of experiments was developed based on program goals for technical rigor, student engagement, cost, and suitability for deployment in an online environment. Preliminary results and "lessons learned" from the deployment of these experiments in an online instructional format are discussed, as well as recommended next steps for the development of a research-based online physics laboratory curriculum.

Introduction

OPPORTUNITIES FOR ONLINE EDUCATION continue to expand. The most recent report of the Babson Survey Research Group shows online learning enrollment increasing at more than ten times the rate for post-secondary education overall, with 31% of all students in higher education now enrolled in at least one online course.[1] The availability of online opportunities is becoming pervasive, with nearly two-thirds of institutions offering face-to-face undergraduate-level courses now offering similar courses online.[2] This availability of online courses and programs, however, varies significantly by discipline. More than a third of all institutions offering full degree programs in business, computer/information science, or Liberal Arts/General Studies also offer full degree programs in the same disciplines completely online.[3] However, less than 10% of all US undergraduate institutions offering physics courses provide even one section of an introductory physics course in an online format.[4]

As online learning continues to make inroads into all disciplines, research-based methods will be needed to assure the quality of the online learning experience keeps pace with the quantity of online learning opportunities. A significant body of literature exists regarding the science of face-to-face undergraduate physics teaching and learning,[5] with gains in standardized tests and large sample sizes providing objective evaluation criteria for competing instructional approaches.[6,7,8] Similar data are scarce, however, for online physics instruction,[9,10] with almost no published literature comparing measureable, objective educational outcomes in online and face-to-face physics laboratory courses.[11,12,13] The result could provide the makings of a "perfect academic storm" as physics departments feel pressured to provide online physics courses with insufficient data on best practices and/or the benefits and pitfalls of competing online education strategies, especially with regard to online physics laboratories.

The American Association of Physics Teachers (AAPT), in a position paper on physics labs, lists the following as goals for introductory lab programs: 1) engage students in the experimental process, including experimental design, 2) develop experimental and analytic skills, 3) advance conceptual learning, 4) assure that students "understand the role of direct observation in physics and to distinguish between inferences based on theory and the outcomes of experiments," and 5) develop collaborative learning skills.[14] Anecdotal evidence and informal survey responses suggest faculty are concerned that online laboratory learning may equate to the substitution of simulations for traditional laboratory experiences or the elimination of lab experiences altogether, mitigating against AAPT goals 1, 2, and 4. In this effort it is shown, however, that online laboratories that include hands-on, student directed, student implemented experimentation could meet all of the AAPT's stated goals, within the constraints for cost, technical rigor, and accuracy appropriate for an undergraduate-level introductory physics course.

This paper proceeds in three parts. Part 1 describes two surveys; the first assesses the current level of availability of introductory physics courses and labs in fully-online formats, and the second identifies the methods used to provide online physics laboratory experiences. Part 2 explores the feasibility of developing a set of "hands-on" student centered physical experiments that could meet the AAPT Guidelines and be deployed in a fully-online undergraduate physics laboratory course. Part 3 examines the initial results of using a subset of these experiments, both in a traditional face-to-face laboratory and as fully online exercises. Finally, "lessons learned" from the process are documented, as well as conclusions and recommendations for next steps in the development of a research-based online physics laboratory curriculum.

Part I: Surveys

According to the US Department of Education, there were 4495 post-secondary degree-granting institutions operating as of 2010, the most recent year reported.[15] In a previous effort, the author conducted a proportionate survey of 398 of those institutions offering undergraduate introductory courses in physics, to assess the level of availability of fully-online introductory physics courses and laboratories. The ratio of two-year to four-year institutions was approximately the same as the ratio of two-year to four-year public institutions for the same period. The survey results revealed that, of the 398 institutions offering introductory undergraduate physics courses, 38 (9.5% ± 2.9%, to the 95% confidence level) offered at least one similar physics course online, and of those, approximately half (15, or 3.8% ± 1.9%, to the 95% confidence level) offered the corresponding laboratory course, or the lab portion of the same course, in an online format.[4] These data indicate that physics courses have significantly lower incidence of online offerings, compared to all other disciplines reported by Allen *et al*.[1,2] Further analysis of the survey data showed no statistically-significant dependence of the results on the status of the institutions as two-year or four-year colleges/universities.

In this current effort, a similar survey was conducted of 311 accredited two-year institutions offering introductory physics courses in traditional (face-to-face) formats, to assess the changes in availability of introductory physics instruction online from Spring 2010 to Spring 2012. Results were further broken down by the type of introductory course (conceptual, algebra/trigonometry based, calculus-based). Broad courses in physical sciences, as well as courses in astronomy, meteorology, oceanography, geology, and/or earth sciences were excluded. Course schedules for the Spring 2012 semester for each institution were reviewed to identify the physics courses taught by type, as well as the modalities by which the courses were offered (self-reported by the institutions as classroom, hybrid, or online/web-based). The results showed a small but statistically significant increase in the availability of online physics courses and laboratory classes, with 34 (11% ± 3.5%, to the 95% confidence level) reporting at least one available section of introductory physics offered online and 21 (6.8% ± 2.8%, to the 95% confidence level) offering at least one section of an introductory physics laboratory course in a fully online format. Even with this increase, the results still demonstrate physics significantly lagging all other disciplines reported in the availability of online educational opportunities.

Because the total sample population of schools offering physics courses online was relatively small (34 institutions), a third survey was conducted. The third survey targeted only those institutions offering introductory physics courses fully online, and sought to identify the methods through which the corresponding laboratory content is presented. The second and third surveys were combined to provide a sample of 66 non-duplicative institutions offering or planning to offer fully-online introductory undergraduate physics courses within the next two years. At 26 of the 66 institutions, all corresponding laboratory work is required to be completed on-site at the campus. Students must either attend a traditional on-campus laboratory course, and so complete discussion and instruction online but perform experiments on-campus (web hybrid approach), or attend an on-campus week or weekend laboratory intensive to perform multiple lab exercises in a condensed time (“boot camp” approach). Thus, for these institutions (39% ± 12%, to the 95% confidence level of institutions offering introductory physics courses online), students complete identical experiments, with identical equipment and supervision, as their peers taking physics courses in a traditional format. The other 61% of online physics students (± 12% to the 95% confidence level) experience a variety of non-traditional approaches towards achieving the goals and learning objectives of the laboratory portion of the curriculum.

Besides traditional (on-site) physics labs, the third survey identified four additional categories into which these approaches fell.

The first approach identified was **video analysis** of instructor-supplied videos of experimental procedures. In some cases, the videos showed instructors performing the experimental procedure, with the measurement data either read by the instructor or the measurement device displays shown in the video for students to read. Other approaches to video analysis included an instructor-supplied video of an object in free-fall, or ‘launched’ in ballistic motion. The students then used commercially-available or educational-commons video analysis software to determine the position, velocity, and acceleration of the object as a function of time.[16] In each case, the student was removed from the experimental design and the hands-on aspects of the experimentation.

The second approach identified was the use of **virtual labs**. In this case, students performed laboratory exercises using a model of the actual physical phenomena, or “virtual” instrumentation that the students were required to manipulate on a computer screen.[17] Respondents were divided between using publically-available simulations, such as those developed by the Physics Education Technology (PhET) Project at UC Boulder,[18,19] privately-developed simulations, or a combination of the two.

The third approach identified was direct, **hands-on** student experimentation performed off-site. Students purchased or borrowed equipment from the institution, or purchased materials from commercial sources, to perform experiments at home. Commercially-available equipment was either purchased as a "kit" from a specialty supplier, or acquired by student purchase of readily-available household items. Of the off-campus lab approaches, this one most closely mirrored the methods and degree of student involvement in the experimental process of the traditional on-campus labs.

The final approach identified was the use of **remote labs**. In this approach, students operate laboratory equipment directly through Internet-based remote control, with real-time video cameras providing direct feedback and immediate observation of measurements and results. A standard approach to distance learning in the engineering community during the past two decades,[20,21] remote labs are only beginning to enter the mainstream of physics education.[22]

A more detailed analysis of the survey results showed that nearly all institutions offering online physics laboratories used a combination of two or more of these approaches. Only four of the nearly four hundred total institutions surveyed across Surveys I and II identified online physics laboratory courses that consisted of simulations only. Thus, the overwhelming majority of introductory physics laboratory students, both in traditional face-to-face lab courses and in online lab courses, experience direct, hands-on experimentation with physical phenomena and measurement techniques.

Part II: Kit Development

For the second part of this effort, the "kit" approach to hands-on, direct experimentation in an online format was chosen for further development. Experiments were considered based on specific standards for cost and appropriateness. These standards limited consideration to experiments that 1) were relevant in scope and content to the curriculum of a first-semester introductory physics course, 2) were of appropriate complexity and depth for a college-level course, 3) would provide sufficient accuracy for student analysis and student satisfaction, 4) could be accomplished semi-autonomously by college students in a distance format (*e.g.*, from home, communicating with instructors via e-mail or online chat, only), 5) required direct, hands-on interaction by students with the experimental process, and 6) could be accomplished with inexpensive or readily available materials at a total cost to students for ten such experiments commensurate with the price of a single textbook. The fact that ten post-secondary institutions offering "kit"-based hands-on online introductory physics laboratory courses were identified in the surveys, with average price-to-student of $130 for an equipment kit, showed immediately that the cost and content goals of this effort were within the current state-of-the-art.

A first-semester introductory physics course usually covers the topics of kinematics (velocity, acceleration, one- and two-dimensional motion, free-fall, and projectile motion), mechanics (Newton's Laws, forces and equilibrium, torques and rotations, gravity, conservation of energy, conservation of momentum), thermodynamics (ideal gas behavior, heat capacities and calorimetry, phase change, thermal transport, simple engines and efficiencies), fluids (hydrostatic and Bernoulli's equations, Archimedes' principle, viscosity, relationships of pressure, force, volume, and density), and simple harmonic motion and waves. A first-semester physics laboratory course typically includes eight to ten experiments, covering a cross-section of topics from this set. A selection of ten experiments covering this material, with an average equipment cost of $15 per experiment, would meet this effort's goals for appropriate content and cost commensurate with the price of a typical college textbook.

According to comments expressed in the Part I surveys, the primary objection by faculty to offering undergraduate physics laboratory courses online is the perceived lack of hands-on interaction by students with appropriate lab equipment. The sophistication of equipment currently available to the average college-aged online learner, however, far exceeds the level available at most college campuses just 30 years ago. All online learners, for instance, have access to a computer with an Internet connection, and the overwhelming majority of these have sound cards that sample at a standard rate of 44.1 kHz, far higher than the sampling rate of high-end introductory physics laboratory data acquisition systems. Coupled with a standard audio input device (microphone), the computer sound card provides students with the capability to time experimental events to within a few thousandths of a second.[23]

A standard computer soundcard, microphone, and collection of free software were used in experiments for this effort as a timing system accurate to one one-thousandth of a second or better. An open-source, General Public Use sound recording and editing software product called Audacity[24] was used to audio-record experiments and determine the time intervals between different experimental events. Figure 1 shows a screen shot of an Audacity recording of a golf ball being dropped from a known height at the same instant the person holding the golf ball said the word, “Time.” The start of each event (the word and the sound of the golf ball hitting the floor) is clearly seen in the recording track shown. Figure 2 shows a zoom-in window of the sound of the ball hitting the floor. Zooming in allows accurate reading by the software user of the precise time of the event. A subsequent reading of the time for the start of the drop allows a very accurate determination of the difference between the two; *i.e.*, the time for the golf ball to fall the known distance. Trials of this simple approach in a home environment yielded very consistent results, with calculation of the acceleration due to gravity repeatedly achieved to within 2% of the accepted value.

A second experiment was completed using the same timing method to investigate the principle of Conservation of Energy. A common first-semester physics experiment uses a motion detector to measure the heights of consecutive bounces of a ball. The ratio of the heights of consecutive bounces is related to the Coefficient of Restitution (COR), a measure of the mechanical energy dissipated in the collision of the ball with the floor. By Conservation of Energy, the ratio of consecutive bounce heights can be calculated using the ratio of the velocities of the ball before and after it bounces. By application of simple kinematics (ignoring air resistance), this quantity is also related to the ratio of time between consecutive bounces.

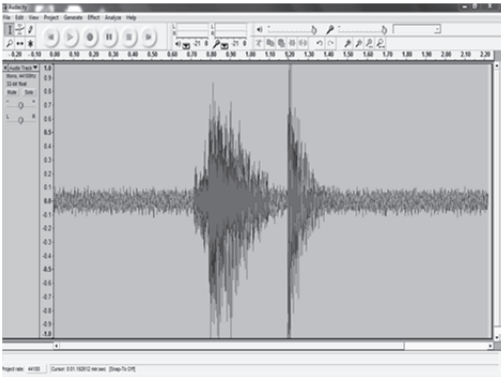

Figure 1. Recording of the time of free-fall for a ball released from a known height. First and second sounds shown are the release and end of flight, respectively. Data recorded with standard PC microphone, soundcard, and Audacity audio recording and editing software.

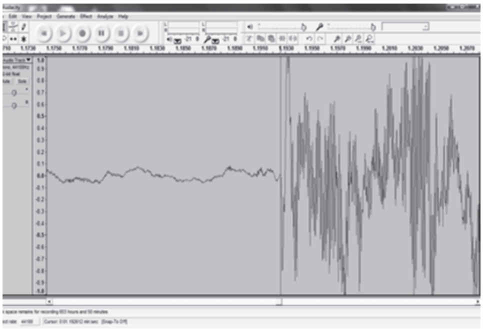

Figure 2. Zooming in to one sound event permits the time to be read to one ten-thousandth of a second.

In the second experiment, the Audacity software and computer sound card were used to determine the COR, and from this, determine *g*, the acceleration due to gravity.[25] The sounds of three consecutive bounces of a golf ball dropped from a known height were recorded using the Audacity software. The absolute times of each bounce were used to determine the time interval between the first two bounces and the time interval between the last two bounces. The COR was calculated from the ratio of these intervals. The timing information was also used to calculate the velocity immediately after the first bounce. Relating this to the initial potential energy and the percent of mechanical energy dissipated in the collision (determined from the COR), the acceleration due to gravity was determined. In trials in a home environment, this method consistently produced measurements of '*g*' within 1% of the accepted value.

These first two experiments investigated the topics of free-fall in constant acceleration, the kinematic equations, conservation of energy, and inelastic collisions. The experiments were completed in times commensurate with standard on-campus physics labs. Total estimated costs for all equipment required for both experiments (one golf ball and a measuring tape) was under $4. These experiments met or exceeded the goals for online introductory physics experiments, identified at the start of this effort.

While cell-phone texting has become the bane of undergraduate face-to-face instruction, the explosive growth and fierce competition in the cell phone industry provides great potential benefits to online learners. About 90% of all Americans aged 18 to 34 own a cell phone,[26] with cell phones increasing in the frequency and quality of applications offered. Almost all cell phones now include a stopwatch feature with one one-hundredth of a second resolution. Many newer devices also embed digital still and video cameras with resolution of up to 30 frames per second.

Combining cell phone video recording with readily-available free software for screen capture and frame-by-frame playback provides another method for accurate experimentation in the home environment. In the third home experiment performed for this effort, a kitchen table was tilted by placing two identical telephone books under the legs on the table's longer side. A low-friction toy hovering on an air cushion[27] was given an initial horizontal velocity on the table top, and the toy's motion was recorded using a cell phone camera. Figure 3 shows the motion of the toy in a series of frame-by-frame screen shots.

The video of the toy's motion was imported into Tracker,[28] an open source software product made available freely for non-commercial, educational purposes. The software allows the user to identify the location of an object of interest in each video frame, and use the pixel count and a reference length to map this location into a calibrated x-y coordinate system. Data can be exported and copied into other programs, or graphed and processed within Tracker to determine linear and angular velocities, accelerations, and momenta. Figure 4 shows screen shots of the resulting video and corresponding graphs of x- and y-locations versus time for the toy. Note the constant velocity of the object in the horizontal direction, with a clearly parabolic graph for the vertical data.

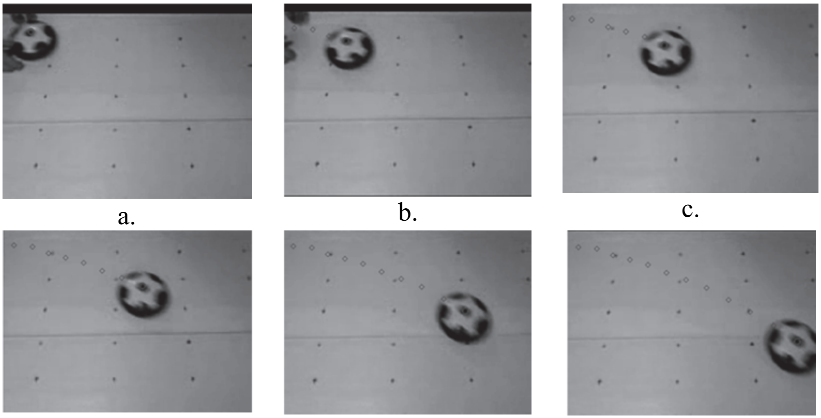
a.
b.
c.
d.
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Figure 3. Motion of a frictionless toy given an initial horizontal velocity across a tilted table

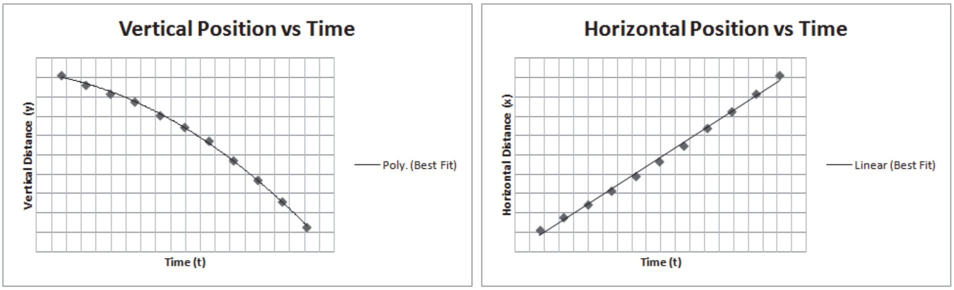

Figure 4. Position data for projectile motion, interpolated using Tracker video analysis software. Notice the constant horizontal velocity (linear graph of x-vs-t) and constant vertical acceleration (parabolic graph of y-vs-t).

Video analysis can be used in a wide range of introductory physics lab applications. Starting the toy from the lower left corner of the table, for instance, would allow the determination of the initial velocity and angle, while trigonometry and the kinematic equations could be used to predict the total distance traveled and x- and y-components of velocity at subsequent positions. Releasing a ball from rest and allowing it to roll down the table in a straight line from top to bottom would mirror the behavior of an object in free-fall. In a variation on this last approach, a single AA battery was released from rest and allowed to roll down the length of the table under the influence of gravity, then compared to the behavior of other rolling objects. An inexpensive caliper would permit the correlation of the accelerations to the objects' moments of inertia.

One of the factors limiting the cost and accuracy of the commercially-available kits was the high prices of calibrated weight sets. Most kits used less-accurate, less-expensive spring scales instead, or a very limited number of calibrated weights. A review of commercial laboratory supply vendors found calibrated weight sets typically costing \$50 to \$70, with a single vendor offering a lowest price of \$25 for a set of hooked masses. Digital scales developed for the jewelry business, with capacity suited for lab applications and resolution of 0.1 grams, however, are now available for under \$20.[29]

With the growing availability of digitized consumer products, such as video cameras, timing devices, software, and scales, the quality and accuracy of home laboratory experiments are now only limited by the creativity of the physics lab instructor. In addition to the free and low-priced items already described, a list was put together of equipment available from multiple vendors and suited for use in home experimentation for a web-based introductory physics course. The final list included a measuring tape, several balls and steel bearings, a plastic caliper, a digital scale and calibration mass, wood blocks and screw-in metal eye hooks, a 1.5 ft. section of 1 x 6 board, 2 spring scales, an edge pulley and table clamp, a stand and right-angle clamp (two preferred), a tandem pulley, a balance stand and three knife-edge meter-stick clamps, a graduated cylinder, an aluminum calorimeter, thermometer measuring −12 °C to 100 °C, a syringe (without needle) and Luer lock cap, two springs, a half-meter stick, a protractor, a spool of thread or string, a push-pin, paper clips, fishing weights, tape and scissors. With the software and techniques described above, this equipment could be used by online students to perform more than twenty college-level experiments spanning the entire range of topics covered in a first-semester introductory physics course. A review of prices offered through a limited number of laboratory equipment suppliers resulted in a price estimate for the entire equipment list of about \$170. Additional cost savings could be realized by economies of scale and by reducing the number of experiments from twenty to eight or ten.

Part III: Student Trials

In the third part of this effort, the first two experiments described in detail in Part II were developed and tried with undergraduate students in an introductory algebra/trigonometry-based physics lab course. The results provided insights into both the strengths and the weaknesses of the chosen approach.

In the first trial, students in a traditional face-to-face physics laboratory course completed two experiments for extra credit at home in a simulated online environment. All descriptions of procedures and techniques for the lab exercises were delivered online, and students were only permitted to communicate with the instructor regarding the experiment via online means (chat, email, virtual office hours). This assured adherence to the “do no harm” philosophy, as students’ primary lab learning experience remained unchanged.

Students were provided with a brief tutorial on how to use the Audacity software and given access to written experimental instructions/guidelines. Initial results were astoundingly poor, as students asked questions at a staggeringly low rate, despite instructor availability through scheduled online virtual office hours, chat, and email response times under two hours. Misunderstandings, misconceptions, and computational errors resulted in student-demonstrated percent errors ranging from 2% to 35%, despite consistent achievement of experimental errors of 1% to 2% in the same experiments carried out by the instructor.

As a result of the initial trial, the entire approach to online laboratory development was restructured. First, the simulated online environment was found to be inefficient as a primary means for vetting student experiments for use in an online laboratory course. Student misconceptions only became apparent once a semester, and only after final experimental reports were submitted. A second approach was developed in which students were supplied written and video instructions, then performed the experiments on campus under direct instructor supervision, but with limited/no instructor comment or direction. Direct instructor observation and immediate student feedback helped identify areas where instructions were unclear, with the result that instructional materials could be modified, improved, and retested within the week.

Video instructions were developed to supplement the written experimental instructions for one of the pilot experiments. These instructions included animations to explain the underlying physical phenomena. Care was taken to make sure the video instructional tools directly addressed the most common misconceptions and questions students had in the performance of the experiments. The goal was to provide instructional information and background sufficient to allow students to make educated choices in measurement methodologies and analyses, to improve experimental accuracy and validity of conclusions, and to assure students could connect the experiments to their prior textbook/theoretical learning, all with minimal/no direct student-instructor guidance.

In addition to the revised video tutorials, the written materials were redesigned to include interactive questions for students to answer based on watching the video materials and performing experimental steps. A sample set of data was provided, with one modeled calculation, to further clarify the analytic process. Additionally, students were required to participate in the derivation of the relevant formulas through a guided process (written instructions provided some steps, students provided subsequent steps).

In the second and third trials, conducted in a traditional on-campus setting with Instructor supervision, students were given the revised instructional materials one week in advance of the scheduled experiment, and were specifically warned that no questions would be answered that had been directly addressed in the written or video presentations. The outcomes included dramatic improvements in student preparedness (as measured by Instructor observation), student conceptual understanding and confidence (as determined from student feedback), and experimental accuracy (as measured in laboratory reports submitted for grading).

Lessons Learned and Next Steps

Animated theoretical background information and visual lab instructions provide students a significant advantage in preparing for, understanding, and performing lab experiments. They also help students directly tie their textbook knowledge to a practical, physical application. As a result, additional visual lab instructional materials will be developed, for both online and face-to-face implementation.

Beginning physics students with no more than a rudimentary background in algebra and trigonometry are capable of deriving physical formulae for lab applications. This process also helps them understand the significance of the formulae, and how they relate to the theoretical/textbook knowledge they already have. However, students at this level need considerable guidance in this process. Lab instructions should therefore be modified incrementally to include (either through a pre-lab exercise or as part of the in-class lab experience) a guided partial derivation of some of the relevant formulae.

A faster, more efficient methodology was identified for pilot testing of new labs for distance education. In this method, candidate experiments for distance labs are vetted in the traditional classroom, with a competent instructor monitoring and noting the common mistakes and misconceptions in real-time, with limited instructor interaction and re-direction. New labs can then be implemented in a simulated or ‘real’ online environment only after they have been dry-run in class, with modifications of the lab methods and instructions based on the initial in-class tests. Student use in a fully-online environment is still required as a “Next Step” for the full development of the lab exercises explored in this investigation.

The greatest hindrance to the development and improvement of a fully-online physics laboratory program is the lack of objective assessment standards for research-based guidance of the curriculum development process. Objective assessment criteria must be developed to compare the efficacy of competing lab methodologies, for both online and on-campus implementation. Assessment criteria should be informed by the AAPT goals for introductory laboratories[14] and the findings of the National Academies. [30] Correlations should be monitored between different laboratory instructional methods and student retention in the lab course, persistence into follow-on courses, improvements in conceptual understanding, knowledge of the scientific process and methods, and perceptions of and interest in further scientific investigation.

Conclusions

Online learning opportunities abound. Online access to introductory physics courses and labs, while far behind the level of accessibility in other disciplines, is following the same general trend in growth. Multiple methods already exist and are being used to provide undergraduate introductory laboratory programs in a fully-online format. Improved quality in and access to consumer electronics, innovations like the use of video and remodeled laboratory instructions, and student demands for flexibility in scheduling and accessibility will continue to impact the future of the online lab experience.

The quality of the lab program that will emerge in the online arena is entirely up to the physics education community. As said in the AAPT Policy Statement,[15] “Excellent laboratory programs do not happen by chance but require thought and planning. Achieving these goals is a worthy challenge, and their broad implementation will require the best efforts of the physics community.” Rigorous, objective metrics must be devised so that competing online laboratory approaches can be evaluated and improved. Research-based assessments must be interwoven into the development of online physics laboratory programs. The alternative is to accept the dramatic growth in the availability of online laboratory programs, with no objective measure of their educational value or impact on future science learning.

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