A review of upgrades to First-Year Physics Experiments to integrate digital control and utilization of more modern technology.

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Abstract. Hands-on laboratory work is essential in first-year physics education, yet traditional setups can lack precision and adaptability. In this study, we present upgrades to key first-year experiments (air-track, the simple pendulum, and optics-based experiments), to enhance accuracy, interactivity, longevity and student engagement.

For the air-track and pendulum experiments, we developed a custom Windows-based C# software interfaced with Arduino micro-controllers to automate control and data acquisition. This upgrade improves measurement capabilities and allows for greater experimental flexibility as well as longevity and compatibility. In optics, we replaced filament-based light sources with LED's, providing more stable and energy-efficient illumination. The spectral characteristics of the different light sources and their implications for experimental results will be presented.

These enhancements offer a more modernized learning experience, fostering deeper conceptual understanding through improved experimental interaction. We will discuss the advantages and challenges of these upgrades, including reliability, ease of use, and student feedback. By integrating modern technology into classical experiments, we aim to bridge the gap between traditional physics education and contemporary scientific methodologies.

1 Introduction

Laboratory work forms a cornerstone of first-year physics education, offering students their first opportunity to engage directly with physical phenomena and experimental methodology. Foundational experiments—such as those involving linear motion, pendulums, and basic optics—not only reinforce theoretical concepts but also shape students' attitudes toward physics as a discipline. However, many traditional laboratory setups remain unchanged for decades, relying on analog components and manual procedures that can limit accuracy, engagement, and relevance [1].

To enhance both the educational value and longevity of these experiments, there is a need to continually modernize laboratory infrastructure. Integrating digital technologies into classical experiments helps bridge the gap between foundational teaching and the tools students could encounter in contemporary research or industry [2]. Modernized systems offer students more accurate and immediate feedback, enabling them to focus on underlying physical principles rather than the limitations of manual measurements. Upgrades such as digital control, automated data acquisition, and LED-based illumination not only improve measurement precision and reliability but also simplify maintenance and reduce long-term operational costs. Many older components—such as filament lamps, analog meters, and LPT-based PC interfaces—are increasingly obsolete and difficult to replace. In contrast, modern micro-controllers and PC interfaces offer long-term compatibility with current operating systems (e.g., Windows 10/11) and greater adaptability across a range of experiments.

Beyond technological improvements, such upgrades also enhance student experience. Exposure to modern tools builds confidence in handling scientific instrumentation and cultivates technical skills transferable to future academic or professional settings [3]. Moreover, developing many of these upgrades in-house allowed us to tailor solutions to our instructional needs while avoiding the constraints and costs of commercial educational lab equipment [4].

In this paper, we present a set of practical upgrades implemented in several cornerstone first-year experiments: the air-track, the simple pendulum, basic optics (light-box and optical bench) and wavelength of light. We detail the design, implementation, and educational motivations behind each upgrade, and discuss the impact on teaching, learning, and long-term laboratory management.

2 Optical Experiments

2.1 Optics with a light box and optical bench

We present two experiments where we exchanged the light sources from incandescent filament lamps to LED sources. The first consideration is to make sure that the replaced light source fulfill the basic requirements in terms of light spectrum and intensity required by the experiment. To this aim the spectra and intensities were measured for both the original incandescent as well as the new LED light sources. All optical light spectra were measured and confirmed using the PASCO Spectrometry App (Version 2.5.1) and a Bluetooth connected PASCO Spectrometer PS-2600 in "Analyze Light" mode. As can be seen in Figure 1, the new LED source offered both a higher intensity as well as a more balanced white light.

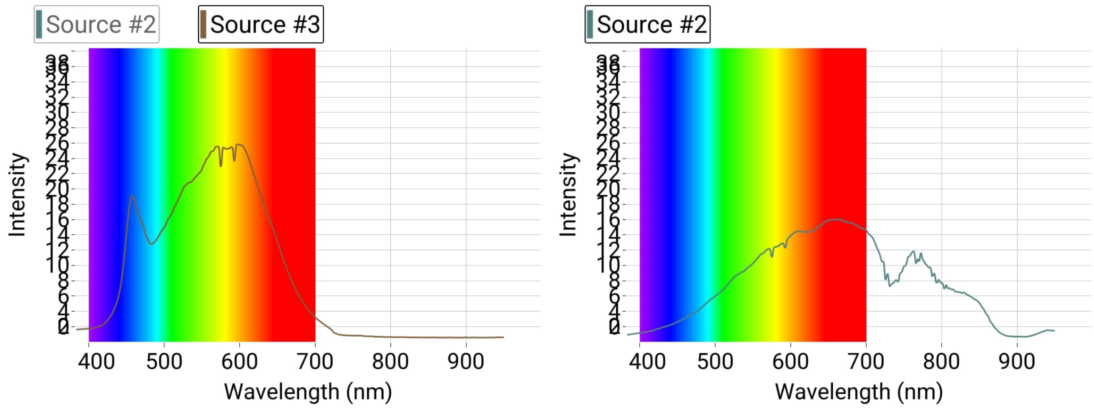

Figure 1: Spectral comparison between light sources, with (*left*) the new LED source (Source #3), and (*right*) the original incandescent light sources used in the optics experiments (Source #2).

The in-house design and build of the new LED sources also allowed us the opportunity to design an effective light housing to screen and direct the light as needed (Refer to figure 2). This reduced experimental and laboratory environmental disturbances due to bright lights visually impairing students relative to the experiments and their surroundings.

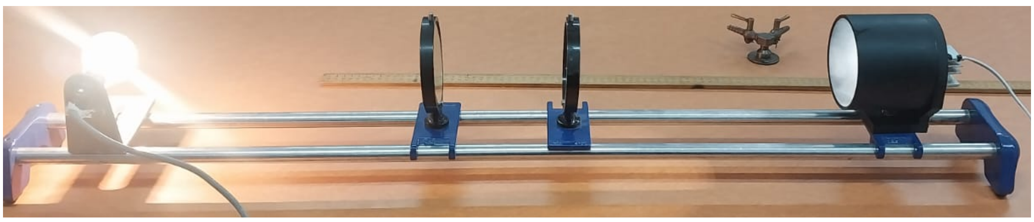

Figure 2: Visual comparison between older incandescent light technology and the new LED based light source as implemented on the optical bench experiment.

The greater intensity improves visibility of light ray's for tracing as well as optical effects such as magnification and reflection. The more balanced white light also results in an improved visual rainbow produced during diffraction through a prism setup (See figure 3).

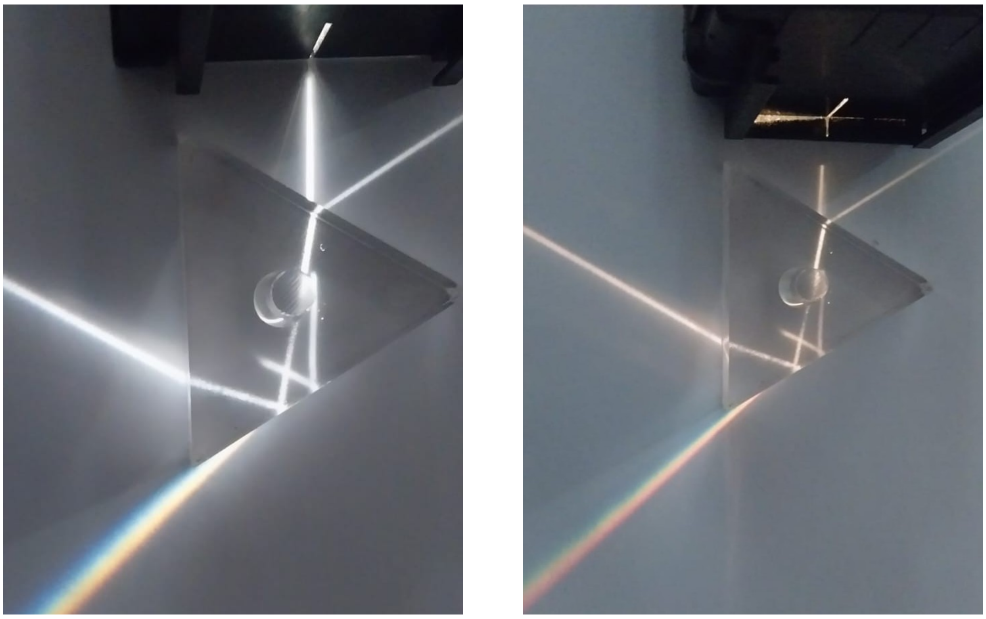

Figure 3: Visual comparison between light source color, luminosity and prism diffracted rainbow, with (*left*) the new LED source, and (*right*) the original incandescent light sources used in the optics with a light-box experiment.

2.2 *Wavelength of light*

The wavelength of light experiment was for many years done using an incandescent light-bulb with a continuous spectrum and an in-house made double slit using an aquadag coated glass plate onto which double-slits were made using a pair of razor blades. The basic setup resulted in interference patterns which were inconsistent between experiments and difficult to measure. A simpler and more repeatable approach was sought, in conjunction to a narrower spectral peak and better light source control per wavelength region. The experimental setup with the new narrow band LED's (Red, Green, Blue) and using a diffraction grating (refer to figure 4), allows for the measurement of the required values as needed by the geometry and equation in figure 5. This setup allows for determination of either the wavelength of the diffracted light λ, or conversely given the wavelength, the diffraction grating constant d.

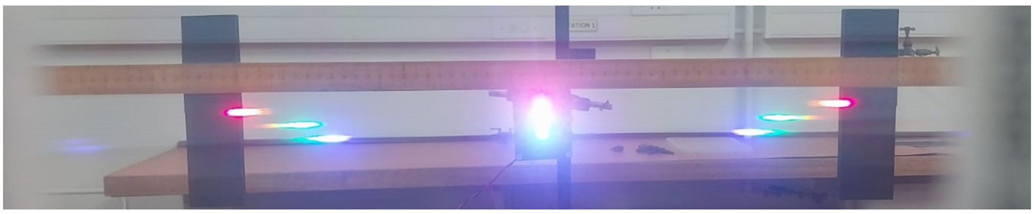

Figure 4: The diffraction images of the three LED's as seen through the diffraction grating, i.e. the student's perspective.

As an exercise to prove the experimental concept and consistency the following measurements and analyses were conducted. Refer to Table 1 for all measurements and results. Using the determined maximum intensity wavelength peak for the red LED ($\lambda = 651nm$) with the PASCO Spectrometer, the diffraction grating constant d was determined experimentally. This experimentally determined diffraction grating constant d was then used to experimentally determine the wavelength values for green ($\lambda = 522nm$) and blue ($\lambda = 461nm$) light within an experimentally acceptable error range $2 - 3\%$ from expected values based on peak position for the green and blue LED's.

$$\lambda = \frac{d}{m} \sin\left(\tan^{-1}\frac{y}{D}\right)$$

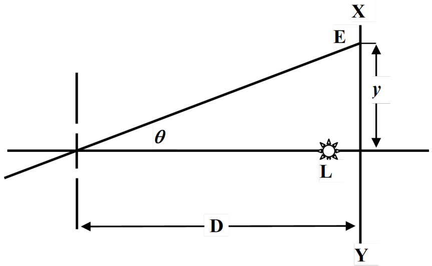

Figure 5: Equation used in the wavelength of light experiment, alongside the geometry of the setup.

Table 1: Calculation of d and λ using experimental data

Section	y_{avg} (mm)	CD (mm)	$\sin(\tan^{-1}(y/CD))$	d or λ (m)	Expected / Error
Red (651 nm)	254.5	750	0.32134	2.03×10^{-6} d_{expected}: 1.667×10^{-6} Error:	lines/mm: 493.61 lines/mm: 600 18%
Green (λ)	207	750	0.26605	λ: 5.39×10^{-7} Error:	Expected: 5.22×10^{-7} 3%
Blue (λ)	178.5	750	0.23153	λ: 4.69×10^{-7} Error:	Expected: 4.61×10^{-7} 2%

3 Mechanical Experiments

3.1 Universal interface and control software

A modern day trend in laboratory products is to makes use of an universal interface between experimental equipment and the computer. This approach simplifies experimental setups as it reduces the amount of unique equipment required to run multiple experiments. To this end a new in-house universal interface between the experimental equipment and the control computer was developed. This interface utilizes an Arduino to manage and control the different components based on connected equipment and user input, where-after it provides feedback to the user. The new interface makes use of an USB connection to the computer which acts like a virtual COM port. The older interface hardware that was unique to each specific experiment utilized either LPT or RS232 COM ports. Refer to figure 6 for a visual comparison between the older and the new interface controller design. The interface and control software is structured as follows: The Arduino controls (set / get) all the physically connected devices, e.g. photo-gates, relays, electro-magnets as well as internal timers for timing measurements. The control software for the Arduino is a C# windows forms application that links the user to the Arduino via various input and control objects that can send commands and receive feedback and display that feedback for use in plotting and calculating values.

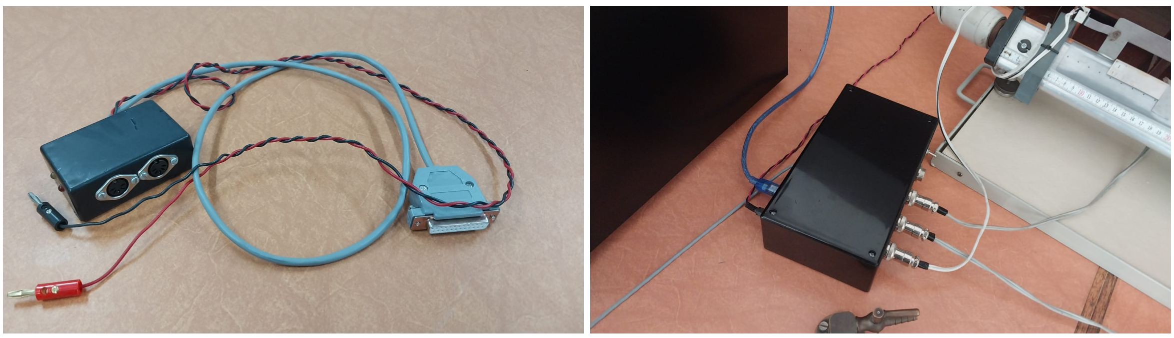

Figure 6: (*left*) Example of what the original air-track controller looks like. (*right*) New universal controller that interfaces with either the air-track equipment or the simple pendulum equipment.

The user software to the interface controller (refer to figure 7) has a variety of functions and capabilities, including the ability to run diagnostics on specific components, i.e. testing photo gates, switching relays and electromagnets. It also provides the ability for configuring the specific experiment that is to be done, i.e. air-track or pendulum. Once configured the experimental sequence can be started, where-after measured values can be retrieved and used to complete a table and plot the values. This can then be utilized in further educational activities such as trend identification, comparative analysis and etc.

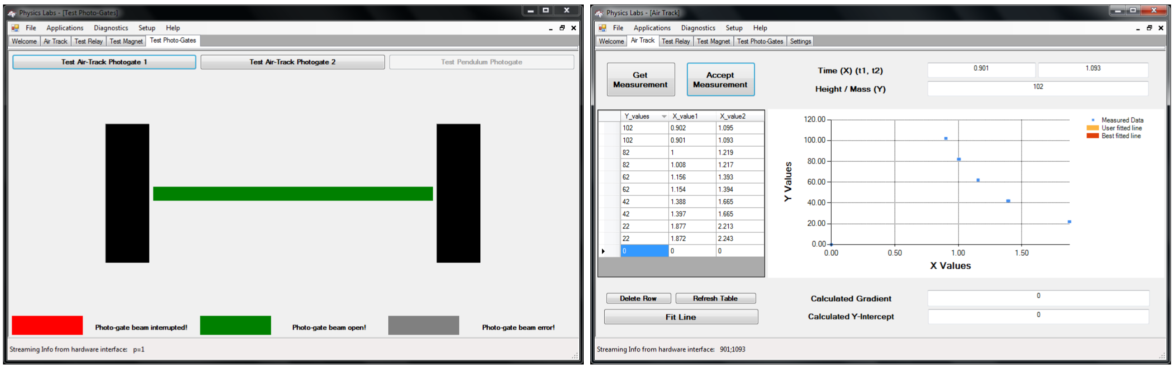

Figure 7: (*left*) Uni-controller interface software with the tab for the photo-gate diagnostics open. (*right*) Uni-controller interface software with the tab for the air-track experiment open with some measurements displayed.

3.2 The simple pendulum and the air track

To test the consistency and accuracy of the new Arduino-driven experimental control and measurement processes, a series of experimental runs were completed for the air-track and simple pendulum experiments. The experiments were set up and completed similarly to how undergraduate students will perform them. For the air-track, the following experimental setups were run: determining the relationship between the acceleration of a body and the force causing the acceleration (Force versus Acceleration), and determining the relationship between the mass and acceleration when a constant force is acting (Acceleration versus inverse of the mass). As the whole experiment revolves around Newton's Law, $\sum F = ma$, the expected outcomes should be a clear linear relationship in each case. The acceleration values are calculated from times measured between set displacements, with the timing triggered when the glider is released and measured when it breaks the photo-gates. Because there are two photo-gates available along the travel path, two time values can be measured per setup. To ensure stability the blower is started and allowed to stabilize for 5 seconds before each run of the glider.

For the simple pendulum, the experimental setups focused on the relationships between the length of the pendulum, the amplitude (starting angle), and the period of oscillation, i.e. $T = kl^z$. The first setup is used to calculate the gravitational constant g from the relationship $\log(T) = \log(k) + z\log(l)$, where T is the measured period and l is the measured length. From $k = \frac{2\pi}{\sqrt{g}}$, the value for g can be determined from a linear regression fit to the experimental data. The second setup is used to test the simple pendulum's small-angle approximation and observe deviations at larger angles for the relationship $T = kl^z$. The measured period values are obtained by counting photo-gate beam breaks and timing the intervals between them. As with the air-track, two measurements are made per setup, i.e., the period is measured twice. To ensure stability of the pendulum and minimize start/release effects 10 beam breaks are counted before the periods are measured.

For consistency checks we present in figure 8 the results pertaining to the force vs. acceleration data for the air-track (left) and the period vs. length data for the simple pendulum (right). To check consistency and accuracy, i.e. repeatability of the experiment, the expectation is that for no change between measured setups the variation between measured values should be within acceptable experimental errors. Therefore, if we set the air-track to a specific configuration in terms of mass and force, then the measured acceleration values calculated from times measured to break photo-gate beams for $\Delta\, x = constant$ and $starting\ velocity = 0\ m.s^{-1}$, should have a very small variation. A simple test is to calculate the experimental mean of the standard deviations between measured values for similar setups, e.g. measured travel times for similar heights. The determined mean for the distribution of standard deviations for measured times for the force vs acceleration setup is $\sigma = 0.004243\ seconds$. Similarly for the simple pendulum the consistency can be checked by the deviation of the measured periods per configuration. This was measured at $\sigma = 0.000636\ seconds$.

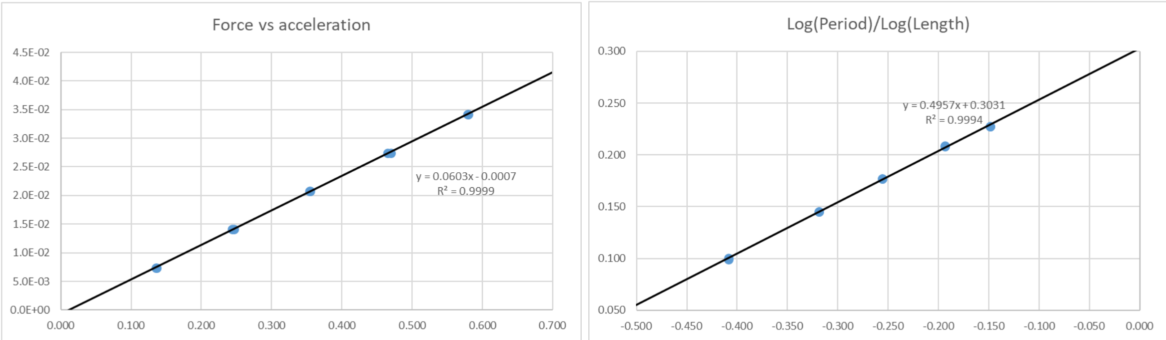

Figure 8: (*left*) Graph of the air-track experimental results based on experimental measurements of force vs acceleration. (*right*) Graph of simple pendulum experiment results based on experimental measurements of variation of the period versus the length.

4 Conclusion

The modernization of first-year physics experiments through the integration of digital technologies has yielded measurable improvements in both functionality and educational value. By replacing outdated analog components with Arduino-driven control and measurement systems, and by adopting LED-based light sources, we enhanced precision, repeatability, and user experience across multiple experiments. These upgrades not only improve experimental outcomes—such as reducing timing variation in mechanical systems—but also foster a more engaging and relevant learning environment aligned with contemporary scientific practice.

In particular, the custom-built universal interface and accompanying software enable streamlined experimental control, real-time feedback, and broader compatibility with modern computing platforms. Likewise, the improved optical setups—with tunable LED sources and better-defined spectra—offer students clearer, more consistent results in wavelength determination and light-based experiments. Importantly, these upgrades were implemented using accessible and cost-effective technologies, allowing for future scalability and customization to suit evolving educational needs.

Together, these developments demonstrate that targeted technological enhancements can revitalize classical physics experiments, bridging the gap between foundational concepts and the demands of modern instrumentation. This approach better equips students for future academic and professional settings, while simultaneously improving the longevity, relevance, and maintainability of undergraduate laboratory infrastructure.

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