PROCEEDINGS OF SCIENCE

Ultimate makeover for an introductory physics lab

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Nowadays, science students face multiple challenges after graduation, and teaching them useful lab skills is a step towards providing the needed support. Thus, the laboratory sections included with the introductory-level Physics I and II courses should provide a student with practical experience and initial laboratory skills that would be further honed by upper-level courses. Emerging from pandemic situation provided the opportunities for a novel approach facilitating a meaningful lab experience to students. This article lists the updated experiments and the innovative methodology that was introduced with the use of the open-source tracker software (https://physlets.org/tracker/). The new methodology has not only expanded the number of possible lab experiments, but provided students with the ability to conduct some of the simple experiments at home using common household items, thus offering both the exciting experience for students and serves as a backup option for lab sessions in case of future restrictions on students' attendance at lab facilities. Additionally, the labs are designed as a progression that introduces additional skills to students such as the use of software for simple analysis, error propagation, creating presentations and more.

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1. Introduction

Both students and educators often underestimate the importance of introductory physics laboratory. Too often, the laboratories simply reiterate the topics previously discussed in lectures. "Research reveals that labs are more effective when their goal is to teach experimental practices rather than to reinforce classroom instruction" [1]. With the recent pandemic, various attendance restrictions and hybrid mode of lab delivery have highlighted the need for a different approach to both the delivery and content of the labs. The approach that was initially evaluated in [2] is now applied to both semesters and fully implemented.

With the support from the grants provided by the University System of Georgia, the two-semester introductory physics lab has been completely modified and expanded to include the following features:

- Labs now follow a progression of their own topics.
- Existing experiments were adjusted to support the progression.
- Tools were introduced to enable remote completion of certain labs.
- Enable students to conduct video and data analysis using any PC.
- Simple experiment videos can be created at home if needed.

This new arrangement has created additional opportunities for student collaboration and independent work while also generating a somewhat higher demand for faculty support and student supervision.

Table 1: Topics progression for the first semester of introductory physics lab.

Lab #	In-person lab	Lab #	Video lab
0	Organizational issues, safety lecture and video.		
2	Introduction of report format and spreadsheet (Excel) basics.	1	How to use Tracker [3-4]: video and small task to complete
4	Error analysis basics, systematic and statistical errors, error propagation.	3	Measure angles in video; systematic and statistical error with Tracker. Error on the slope using linear regression.
6	Plot with error bars, line fit and χ^2in a spreadsheet software.	5	Error propagation and plot of experimental data vs model.
8	Computer-based sensor calibration and readout. Y- and X-error bars in plots.	7	Usage of file import for data analysis in Tracker – using this software for external data analysis.
10	Do a video in lab for analysis at home, also record data from sensors. Compare tracker results with results using sensor data.	9	Create a plot using multiple data series and using different axes; plot of residuals.
12	Finding non-linearity in a pendulum. Analysis is done using sensor data and sine fit in data acquisition software.	11	Measure radius in tracker, center of mass motion, align coordinate system with the inclined plane.

2. Progression of Topics

The complete topics progression for the two semesters is presented without the list of the associated experiments as most of the introductory level lab setups can be adjusted to be used with different topics. Table 1 lists the progression of the topics for the first semester of the introductory physics course labs. Note that certain topics are listed under the 'video lab' heading: these labs involve the analysis of the videos of experiments and can be performed remotely as needed. The videos are provided to students by instructors as creating quality videos suitable for video analysis is complex. Most videos are shot with 480 or 960 frames per second so that the moving objects are not blurred. Example labs for the first semester are listed in [4] as well as Tracker details.

The topics of the second semester listed in Table 2. There are only two video labs as this is the E&M and optics semester. Two experiments suitable for the conversion to the video labs are the e/m ratio for the electron and the magnetic field of the Helmholtz coils – both labs are rather complicated and only exist as one setup for each, making it impossible for all students to conduct these experiments in person regardless.

Table 1: Topics progression for the second semester of introductory physics lab.

Lab #	Lab type	Lab skills description
1	In-class	Review of measurements, uncertainties, χ^2 and error propagation; a procedure for a manual fit in spreadsheet is introduced.
2	In-class	Advanced spreadsheet (Excel) skills, mapping of contour plot of scalar field (electric potential) to experimental plot – simple simulation.
3	In-class	Instrumental error; linear mapping, simplified use of x and y error bars for χ^2, deviation from linearity, use of residuals.
4	In-class	Solving a linear system of equations using computer; complexity reduction using different approaches.
5	In-class	Construction of circuit from schematic, breadboard skills.
6	In-class	Linearization using the reciprocal plot and error bars handling. Using http://www.physicsplot.com/
7	In-class	Non-mechanical oscillating systems, linearization of the exponential plot and error bars handling.
8	Video	Using Tracker for the analysis of a set of static photos with circle radius
9	Video	Fit of a complex data with a model – steps towards Bayesian approach
10	In-class	Error propagation application to angles. Laser safety.
11	In-class	Creating presentation slides instead of the report – how to make a successful presentation

3. Curve Fitting

The most overlooked topic in the majority of the introductory level physics labs is curve fitting. Some still use pen and paper, others use the trendline provided by the spreadsheet software with rare cases of expanding further than that. We have developed the approach that introduces the curve fitting from the basics yet without the full statistical derivation of the least squares minimization that should belong to a statistics or similar class.

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After introducing the basic concept of measurement errors, including both statistical and systematic errors, students are then tasked with plotting the corresponding error bars (labs 3 and 5 in Table 1). At the same time, the Excel function 'linear regression' is used to assess the slope error for the linear fits. In lab 5, students are asked to plot the theoretical prediction and the data with error bars on the same plot and compare them visually. This leads to the introduction of the χ^2 concept in lab 6 that now allows to quantify the quality of the match between the curve and the data.

Two equations are provided to students: eq. 1 is the basic χ^2 definition in the context of the least squares fit, and eq. 2 is the definition of the reduced χ^2, scaled by the number of points in the plot and the number of free parameters in the fit function. For the comparison between any simulated/predicted curve and the measured data, free parameters are set to 0. It's important to note Excel templates are provided to students for all labs where new concepts are introduced.

$$\chi^2 = \sum_{\substack{all\ data \\ points}} \frac{(data - theory)^2}{y\_error^2} \quad (1)$$

Equation 1: The chi-squared equation.

$$\chi^2/ndf = \frac{\chi^2}{(n_{points} - n_{variables\_in\_fit})} \quad (2)$$

Equation 2: The reduced chi-squared equation.

Lab 8 from the first semester introduces the idea that error bars are important both along the x- and y-axis. Yet, the extremely simplified attempt to use them for the χ^2 is only done in lab 3 of the second semester by summing the weighted by both errors perpendicular distance between the fitted line and data points. For the same lab and onwards, computer-based tools are used to do the fits, such as http://www.physicsplot.com/ , python with ROOT or any other software that can account for both error bars and provide the uncertainties for all fit parameters.

4. Conclusion

During the initial testing and the implementing of this approach over the course of the last two semesters, our experience has shown that the online analysis tools are generally well-received by students. Only a few students have reported technical difficulties, mainly when they missed the introduction to the tools in class. Furthermore, according to the students' feedback, online lab experiments are highly preferred over in-class ones, which has led us to expand video labs to encompass 50% of all lab experiments in the first semester.

We see sufficient value in the students' projects and new lab experience to adopt these practices into curriculum. The results of the student satisfaction survey are provided in [4]. All lab materials and manuals are available at [5] and [6] under the free CCBY license.

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