Promoting usable skills and analysis methods via introductory physics labs

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The need for new labs

- "Research reveals that labs are more effective when their goal is to teach experimental practices rather than to reinforce classroom instruction." [1]
- Structure labs to follow their own list of topics that introduce skills in logical order
- Teach students tools to allow some labs to be done remotely (as needed)
- Students able to conduct advanced video analysis and data collection using any PC
- Can create videos at home if needed or desired

Classes may still be in hybrid or similar mode that is not fully in-person → Need to provide support for projects and labs
- For independent work or collaboration

→ Work was performed with support from ALG grant by GA State

Introduced progression of new skills – semester 1

In-class labs

0. Intro lab: organizational issues and safety lecture/video
2. Report format and Excel basics are introduced
4. Into the error analysis, systematic and statistical errors, error propagation.
6. Lab will feature plot, error bars, fit and chi² in excel.
8. use of computer-based sensor readout and calibration. Y and X error bars.
10. Do video in class for analysis at home, and record data from cars sensors. Compare tracker results with results using data
12. in-class exam/report. Finding non-linearity in oscillators.

Video labs

1. How to use Tracker*: video and small task to complete
3. Measure angle; systematic and statistical error in tracker. Linear regression in excel.
5. Features error propagation and plot of data vs model.
7. Features the use of file import and data analysis in tracker – shows that can analyze outside data.
9. A plot with multiple data series and using different axes, plot of residuals
11. Measure radius in tracker, Center of mass motion, incline plane and coordinate systems.

Introduced progression of new skills – semester 2

In-class labs:

1. Review of measurements, uncertainties, χ^2 and error propagation; a procedure for manual fit is introduced. Measuring a table length ☺.
2. Advanced Excel skills, mapping of contour plot of scalar field (electric potential) to experimental plot - simulation
3. Instrumental error; linear mapping, simplified use of x and y error bars for χ^2, deviation from linearity (Non-linearity in Ohm's law)
4. Solving a linear system of equations using computer; complexity reduction using different approaches (irreducible three resistors triangle)
5. Construction of circuit from schematic, breadboard skills (resistor networks)
6. Linearization of the reciprocal fit and error bars handling (capacitance and dielectric constant)
7. Non-mechanical oscillating systems, linearization of the exponential fit and error bars handling. (RC circuit)
10. Error propagation application to angles. Laser safety. (Water index of refraction)
11. Creating presentation slides instead of the report – how to make a successful presentation

Video labs (8 and 9 only):

8. Using Tracker for the analysis of a set of static photos (E over m experiment)
9. Fit of a complex data with a model – steps towards Bayesian approach to analysis (B-field of Helmholtz coils)

- More details are provided in [2], [3]
- All manuals and other materials are available in [4] and [5]
- All fitting is done using https://sos.clayton.edu/physics/chi2

On the fitting and χ^2

Using Excel:

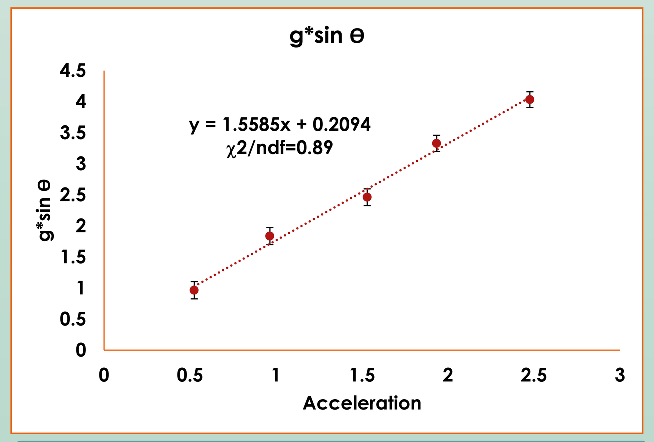


Figure 1. A linear fit to data in Excel with χ^2.

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

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

- A fit to data from inclined plane experiment is shown in Figure 1. χ^2 is calculated with y-error bars only as they are much larger than x-error bars (not visible on the plot).
- Error on slope is calculated using "Regression" tool.
- Data having uncertainties for both y and x axes can't be reasonably fitted in spreadsheet software as none take x-error bars into account. Accounting for them both and obtaining errors on fit parameters is a complicated task.
- We created https://sos.clayton.edu/physics/chi2 website using ROOT and Python as a web interface that can be used by students – sample fit shown in Figure 2 below.
- Figure 3 is the sample histogram with a Gaussian fit. Poisson error bars for each histogram column are assumed.

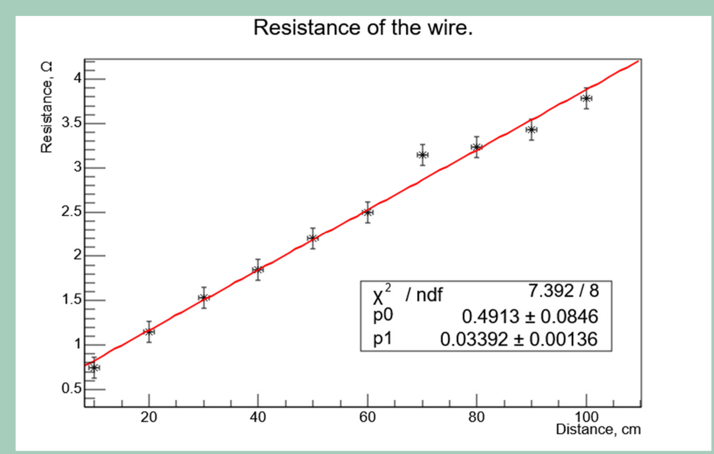


Figure 2. A linear fit to data using online tool.

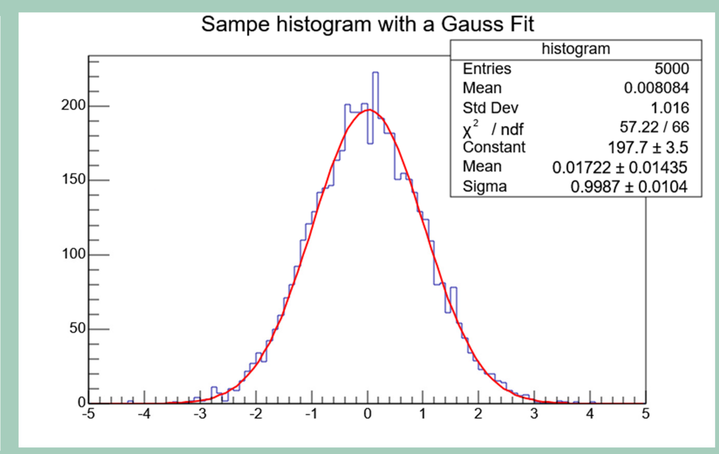


Figure 3. A sample histogram with Gaussian fit.

Tracker software for labs/capstone projects

Advantages of using Tracker-based projects/labs
- https://www.physlets.org/tracker/

Instruction on procedures and data analysis steps
- Via multiple methods:
  - online meeting
  - recorded video with the instructions

Laboratory manuals and supporting materials
- Posted on class site, including several supplemental videos provided by an instructor as needed.

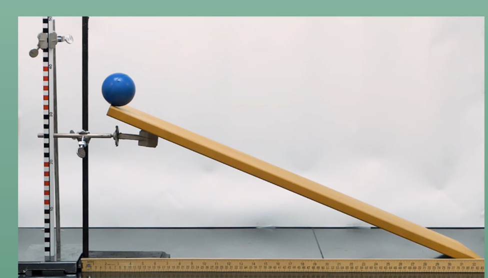
Student options are:
- Create your own video and analyze - for simple labs
- Use instructor provided video for analysis

Analysis
- Can be done at home to support hybrid teaching mode (e.g. 50% in lab/class and 50% online/at home)

Example: Capstone project on moment of inertia of different objects:

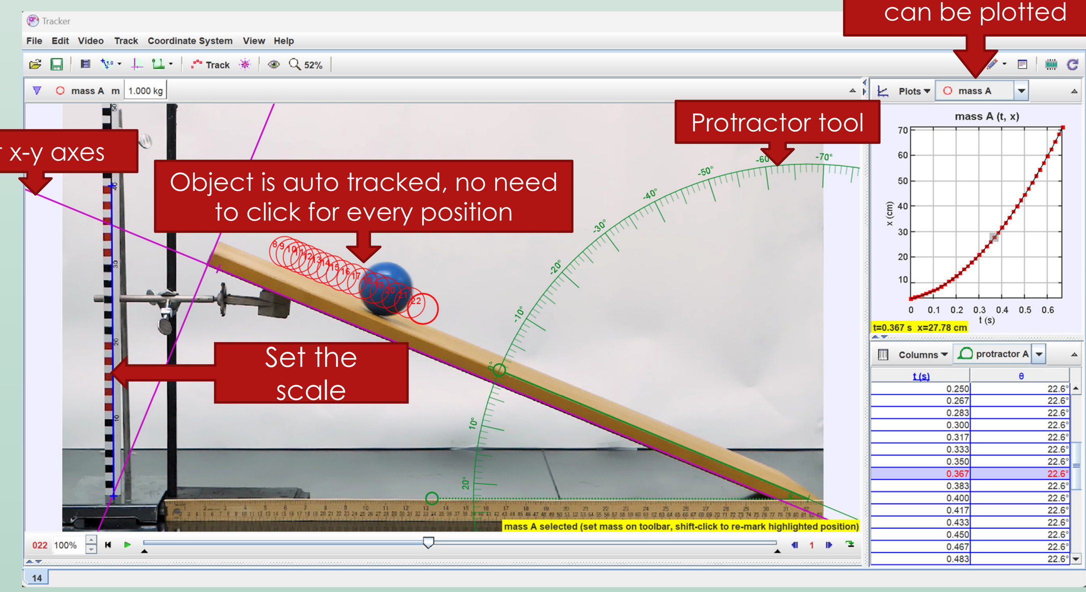
A sample video of rolling hollow cylinder is below

Additional videos are used as a capstone project for Physics 1 course.



	Summary			
		a^{exp} (m/s²)	$a^{theoretical}$ (m/s²)	
	Solid Sphere	1.659	1.618	
	Hollow Sphere	1.347	1.311	
	Solid Cylinder	1.628	1.790	
	Hollow Cylinder	1.287	1.342	

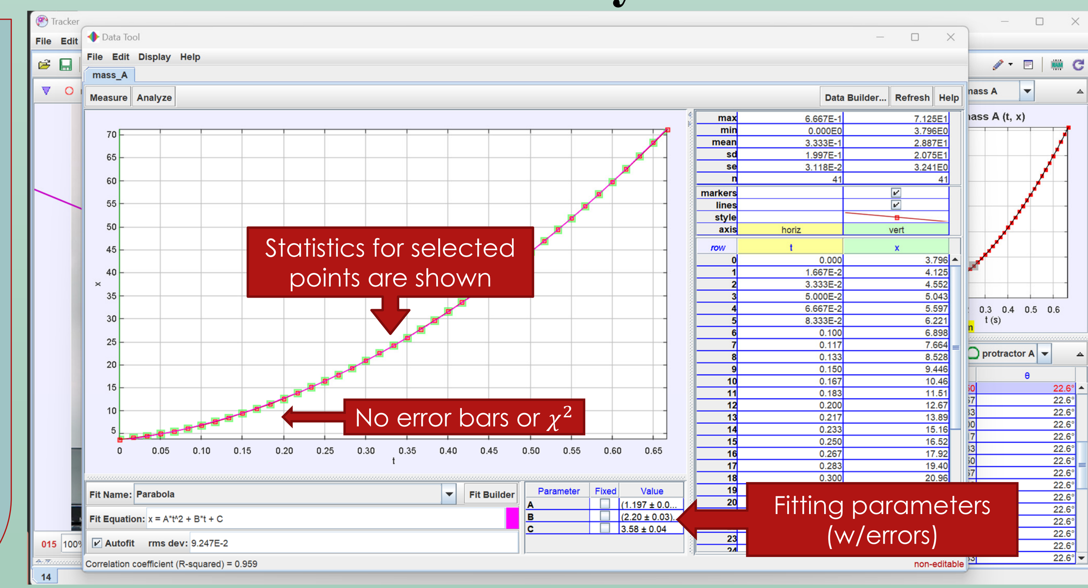
Tracker main screen



- Tracker video analysis screen features various tools, such as:
  - x-y axis setup, scale setup
  - tools like protractor
  - ability to set fps of the video (and time scale)
- Shows a table and plots of different valuables

Tracker analysis screen

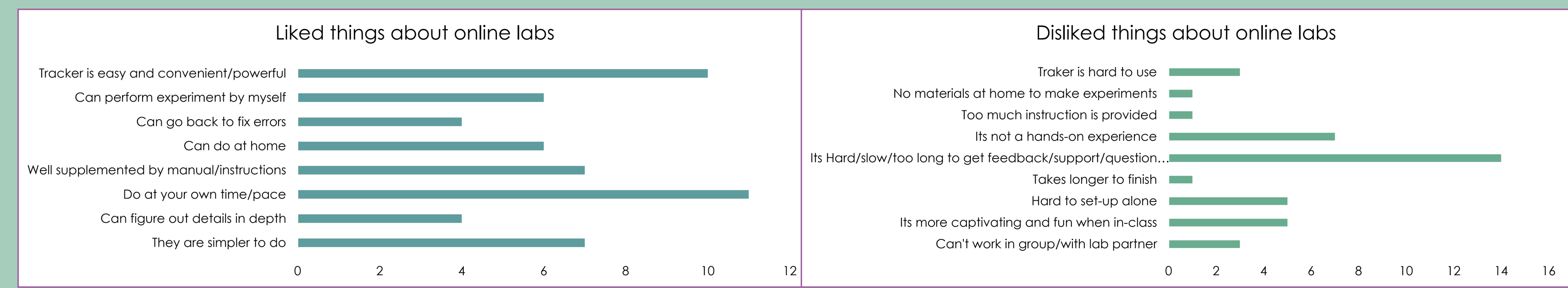
- Tracker allows to analyze data from videos, images, or imported data from .csv
- Fitter features: custom function creation and fit to selected points.
- Errors on fit parameters are provided.
- Lacks error bars altogether.



Survey results about the online labs and use of Tracker

Most students likes using Tracker, doing things at home and their own time and pace

Most disliked thing was that it's harder or much slower than during the class to get the support or question answered by the instructor



Conclusions:

The experience has shown that:

- Online analysis tool is very useful! (Only few students using Safari are reporting technical difficulties)
- Online lab experiments are much preferred, so we plan to expand semester to with more online labs.

We see sufficient value in the students' projects and new lab experience to permanently adopt these practices into curriculum.

The work was completed to create the high-quality videos with high frame rate (480 to 960 fps) for all labs and some extras for lab topics rotation and for use as projects for the lectures part of the course

The lab manuals have been re-written to match new additions

Video manuals for Excel and Tracker have been updated to support the new requirements (CCBY license is used).

- Excel manual: https://www.youtube.com/watch?v=gyvmuZIzwnk
- Tracker manual: https://www.youtube.com/watch?v=IrD10scYpsA

REFERENCES:

[1] Natasha Holmes and Carl Wieman. "Introductory physics labs: We can do better", Physics Today 71, 1, 38 (2018); https://doi.org/10.1063/PT.3.3816

[2] Dmitriy Beznosko, Tatiana Krivosheev, Alexander Iakovlev, "Ultimate makeover for an introductory physics lab", PoS(ICRC2023)1597, ICRC2023 2023/7/25 DOI: https://doi.org/10.22323/1.444.1597

[3] Dmitriy Beznosko, Tatiana Krivosheev and Alexander Iakovlev, "Innovations in teaching of the Physics and Astronomy laboratories", PoS(ICHEP2022)368, ICHEP2022, July 2022

[4] Beznosko, Dmitriy, and Tatiana Krivosheev. "Laboratory Manual for Principles of Physics I." (2023). https://oer.galileo.usg.edu/physics-textbooks/2/

[5] Beznosko, Dmitriy, and Tatiana Krivosheev. "Laboratory Manual for Principles of Physics II." (2023). https://oer.galileo.usg.edu/physics-textbooks/3/