Lab 0. Intro to Work in Laboratory

Goals

- To get an idea of how experiments are conducted.
- To understand the key ingredients for useful lab notes.
- To be able to use the data acquisition software Capstone.
- To be able to efficiently use Capstone and Excel for data analysis.
- To make quantitative comparisons of results with predictions

Introduction

> "*An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer.*" Max Planck

Lab notes should be a shorthand description of the communication with nature. They include the circumstances around the recording of Nature. The formal lab report translates all into an understandable format for the interested outsider.

In undergraduate laboratories experiments tend to be preconfigured and close to ready to use. However, it is useful to have some knowledge how experiments are conceived and conducted. At times equipment may fail or not function as expected or you are asked to add to the experimental plan. Experimental procedures and problem solving methods drive how and what to keep a record of. Success in the undergraduate laboratories requires the generation of understandable lab notes and more formal lab reports. A significant number of experiments rely upon computer controlled sensors and occasionally computer generated control of experiments. Data are acquired with the aid of the computer and then further analyzed. In this lab tutorial key elements of lab notes will be discussed. The software Capstone (for data collection and data analysis capabilities) as well as Excel will be presented. The laboratory experiments "Motion along a Straight Line" or "Free Fall" will be used as demonstration examples. Returning to lab notes, a method to compare results from different sources will be quantified. The five topics are:

- Experiments
- Lab notes
- Capstone and data acquisition
- Capstone and Excel data analysis
- Quantifiable tools to compare results: the *t'*-score

Experiments

College is a chance to use the expertise, time, and resources of the school to gain as much experience and exposure to professional experiences as possible. The lab environment should stand out as a phenomenal place to realize this goal, wherein the means is the acquisition and analysis of physical data.

The resources you will use this year are unlikely to match many resources you will have available in the future. Photogates and other sensors we utilize just do not come up that often. However, the experience that this lab sequence is providing you with is invaluable, at least if we successfully communicate our intentions. We are trying to teach you how to support an argument with data. If you want to convince your boss that having the company provide you with a reserved parking space right outside the door will increase profits, you can do that using the data gathering and numerical analysis techniques we teach you in this class, assuming it is true at least.

Focus on this goal in every lab experiment this semester: Use your equipment properly, know the limitations of the equipment, take careful data, and use that data to support a conclusion. Do not get distracted by the minutia along the way. While textbook based classes may appear to care about the "right" answers and how much you can remember, in a lab course unpredictable things can and will happen. Such oddities are not a distraction or mistake, they are simply one more element to account for and either incorporate or overcome.

What specific things we work with from week to week may seem uninteresting, and are likely not activities you will ever find yourself doing again in your life. But they do represented simplified versions of things you find around you on a daily basis. You are asked to come up with analogous situations to each lab as we go through the semester. For an easy example, when we crash carts into one another to demonstrate Newton's Third Law, that is easily seen as analogous to real car crashes, and also bears a connection to bowling. Being able to see how seemingly different situations bear common underlying physical explanations is one of the hallmarks of successful physicists.

In addition to coming up with analogues, each week you are required to perform unit analysis, and draw a Force Diagram. Developing this habit will assist greatly in the lecture and in many other courses or future endeavors.

These following points are keys to consider as you approach any investigation, and each of the labs for this semester especially. Elaboration/example is provided by discussing the upcoming Linear Motion and Freefall labs:

- *What do you want to know?* Start with the title of the lab. What is to be investigated? Here: How does an object move along a path? Can a simple equation of motion of position versus time make predictions?
- *How to simplify the problem as much as possible?* Driving a car or bicycle from home to work may involve a convoluted path and many parameters. Turns, friction, tire pressure, air-resistance, changes in elevation and more play a role. Make it simple: no turns, no friction, no air resistance, horizontal (vertical) motion or a single steady slope.
- *What do you know about this?* Well, you are about to cover the equation of motion in one dimension. Besides time as the input, there are the initial position, speed and acceleration.

There is a track (or the fall of the ball towards the center of Earth). There is a slope. The object is a cart (or ball).

- *What will happen?* The equation is the prediction. Given the starting conditions you can predict when the cart will reach the end of the track (the ball will hit the floor). For example: "on a level track the cart will neither slow down nor accelerate"; or: "timing the fall of a rock into a well and listening for the splash lets you calculate the depth of the well."
- *What's the plan?*Set up the experiment (which has been done for you). Describe it with a sketch. That should include the essentials only. The cart (ball) and track (the vertical line down) are obvious. What is the orientation of the track? Is it horizontal, i.e. level, or at an angle? Indicate how to measure that. Indicate a direction of positive time or motion. Define the key components and physics parameters (like speed and acceleration). How is the experiment started or triggered? The cart gets a "kick" (the ball is let go without spin). The position is recorded over time. How? Write it down.
- *Time management* No experiment can consume infinite time. Having a sense of what will happen (see the predictions) allows for judgment calls. Decide about where to place measurements along a range of options. Should you focus on one end or the other or change a parameter in equal steps? Where should data acquisition be focused? "Record the cart motion once, three times or 100 times?" "Push gently or hard?" "Focus on the time between first and second bounce of the ball or elsewhere".
- *Execute the plan* Start the data recording. This is where the Capstone program comes into play (see below). Trigger the cart's motion (let go of the ball). Repeat several times. Write down what is done: Kick towards sensor on level track, take 1, take 2, etc. (Drop the ball, take 1, 2, etc.). Write down what happens: "the cart jumps the track (the ball is spinning)", "the cart stops mid track" are some. Print out the data. Label stuff.
- *Analyze the data* Given the physics equations from above, can you "fit" the motion. What are the fit parameters. Note them down. Do not forget units and uncertainties. This, too, involves Capstone. You may have to combine multiple takes and average. This is where Excel comes in handy.
- *Compare to prediction* Did the cart "neither slow down nor accelerate on the level track"? Yes, or no. Would that depend on how carefully you look? This is, where quantitative methods of comparing come in handy (see below for t'-scores).
- *Draw conclusions* Write down the findings. Such as: "The ball dropped with a constant acceleration of $9.8m/s^2$. That value is known with an uncertainty of $0.1m/s^2$."; or "the cart did slow down after all; the acceleration was $-0.02 \pm 0.01m/s^2$." And "Friction was not eliminated completely".
- *What can/should be done in further experiments?* Once you know how to do things, you also can find ways to do it better. That should go here. Sometimes, you can do it right away. That's a modification to the plan. Now jump back to the step of "Execute the plan" for the next iteration.

That's it. Just keep in mind to post timestamps. One per page is sufficient. At every step is better. Print outs should be big, in landscape and full page. Add labels, so you and your grader know what belongs where.

Lab notes

The notes are the written record of your actions, measurements, and observations. Science relies upon data and concrete, verifiable facts. "Having it all in your head" is never acceptable. Thus if something is not in your notes, then it did not happen. Even if the manual told you to do something, and you clearly must have done so in order to obtain information which IS in your notes... if you did not record it, nothing counts. Someone with no access to the Lab Manual who comes across your notes should know what you did, why you did it, and everything that they would need to do in order to repeat it.

- *Headings*: Start with the number and title of the laboratory. List your name, your WSU ID, your lab partner's name, the class and section number (for example PHYS 101 lab 03) and the date. This is invaluable if your notes are lost, or if you need to later prove you were present due to clerical errors in attendance tracking.
- *Timestamps*: List the current time on the right margin of your notes at least once per page. Many labs have different components. List the times at their start points. Timestamps (and dates for longer efforts) help in the organization. External events may contribute to outcomes but are discovered only later. Correlation becomes possible with good time keeping.
- *Be brief*: These are not novels. These are memory aides for you (and the exam) and recipes and procedures to reproduce the experiment. Full paragraphs should not happen at any point.
- *Introduction*: In a **bullet list**, note down the initial steps of an experiment. Start with what is to be investigated. End up at an outline of the plan. Your TA's introductory notes and the materials from lecture, textbook, and lab manual can help.
- *Sketches*: "A picture is worth a thousand words." Sketches, free-body diagrams and drawings are worth more. They leave out all but the essential parts. Make them **big**. Half page sizes are good. Add labels. "Cart", "motion sensor" and arrows with "this way in time and positive direction" are examples. Most of us cannot draw straight lines freehand. If a specific slope is important, note that down. We do not expect artistic masterpieces, so supplement with words whenever your images are inadequate to portray important detail.
- *Math*: Don't just write down equations. Besides an equation using the value "p_{cart}", write down that "p_{cart}" is the momentum of the cart. After all, it could be "power". "F" may be a force but could denote friction. In algebra, include steps. Basically, imagine your physics book math without any annotation. Would that be comprehensible?
- *Taking data*: When recording the motion of a cart along a track, write in you notes what is done: "First run: give cart a push to let it travel from the right towards the sensor". If the data are printed, add labels to the printout for easy correlation.
- *Graphs*: Make them **big**. Full page landscape is the standard. Leave plenty of room to add annotation later.
- *The actual experiment*: Not all of the data collected on the computer may be equally relevant. Only the parts that help the question to nature are of interest. Highlight this part and say so in your notes. For example "the experiment takes place from time = 5 sec to time = 21 sec, as highlighted by the shaded box". If you start the recording of "the basketball falling over time" and then position and let go of the ball, the first part until the ball drops is not part of the **actual experiment**. It's part of the setup. Once the ball bounces out of the field of view of the sensor the actual experiment is over. The rest until the stop button is hit is not part of

the actual experiment. When the cart stops mid-track or hits the end of the track, that may be the end of the **actual experiment**.

- *Relevant in a graph*: Axes must be labeled and have correct units. If you are graphing inverse mass, the units are "1/kg". Label the graph so you and your grader can correlate the graph with the specific notes in the report. The **actual experiment** part should cover at least 50% of the graph area and be pointed out. At times, a separate overview graph may show a full set of data once.
- *Fits and other analysis in graphs*: Line fits will be made to find best matches of functions with datasets. Again, the highlighted sections are important. Results should also be in the lab notes and not just on the graph. Provide the equation of the fit whenever possible (it should always be possible).
- *Results*: Do not records a billion digits unless relevant. This is called significant figures. Any result has a value, an uncertainty and units. You may measure the length of the track and write down to the nearest millimeter. Nobody would even think of using micro or nanometers. The tape measure and the viewing angle play a role. So the nearest precision is a millimeter. That's the uncertainty. "The track is $1.234 \pm 0.001m$ long" is the example. More digits are meaningless.
- *I am going to write it up neatly later*: is not an option. These are not memoirs. These are the life tapes of what is going on in the experiment. Do not leave space for filling in the blanks later.
- *Summary and conclusions*: A summary is not "we measured a lot". A summary repeats the key results and findings that answer the initial question. "The basketball falls with constant acceleration. The acceleration is $9.8 \pm 0.1m/s^2$." "The cart does not travel with constant velocity along a horizontal track. Friction, even though small, is the cause. It is equivalent of a deceleration of $0.015 \pm 0.004m/s^2$." "The equation of motion in 1 dimension predicts the motion within uncertainty of xxx." Up until the summary, your notes are a jumbled mess, and contain lots of extra information. It is now that you sort through the information in order to ensure the reader of the work is getting the bigger picture.

At this point, experiment and notes thought to be complete... you need to look at your Rubrics for the lab. Read over the rubrics and make sure that you have performed something which can be evaluated for each assigned rubric category at least once. In those cases where you have done an action multiple times (like graphs), ensure that every instance is showing your absolute best work. If you included 12 graphs, and 11 of them were flawless, but for one of them you failed to label the axes... you would be evaluated as "Progressing" instead of "Scientific"

Capstone data acquisition

A lot of what you need to know in Capstone is how to set up the specific sensors being used for the week. We will cover new sensors as they are introduced. For now, the important thing that will be used every time is how to display the data from the sensors on the screen so that you can record and later analyze the measurements from each sensor.

When you launch Capstone, it loads with a few template options available to click on, shown in Figure 1. It is uncommon that one of these templates is precisely what you want to use, but the

first three options may occasionally suffice.

Figure 1. From left to right, 1) A table with graph, 2) A graph with two digital displays, and 3) two digital displays.

When you want to have a more specific layout, you will be looking at the sidebar on the far right as in Figure 2.

Figure 2. The primary options of interest in Capstone Displays toolbar

To use one of these displays, you will drag the icon to the center panel of the screen and release. Once you have the display element on screen, all that is left is to assign labels and data. Somewhere, you will see Figure 3 inside the display element. Click on that to get a menu, where you can select which data you want to use.

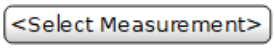


Figure 3. Click on this to get a dropdown and assign data to a display element.

Note that on a Graph display, you will have two places to assign data, one set of data per axis, as well as a spot in the lower left to assign a Title to your Graph, shown in Figure 4.

A few buttons along the top of your graph can be of great use. Looking at Figure 5, button a will auto-scale your display to zoom as far in as possible while still getting all data in view, button b will insert a selected best fit line, button c will add a coordinate reading tool (useful for finding specific values along the graph), and button d will let you place multiple data sets along the Y axis (useful for overlapping graphs to make comparisons).

On page 121 there is a decription on how to use DataStudio, the precursor to Capstone. Most of that information remains relevant and can be of use in the new software as well.

A few other notes not yet fleshed out with images:

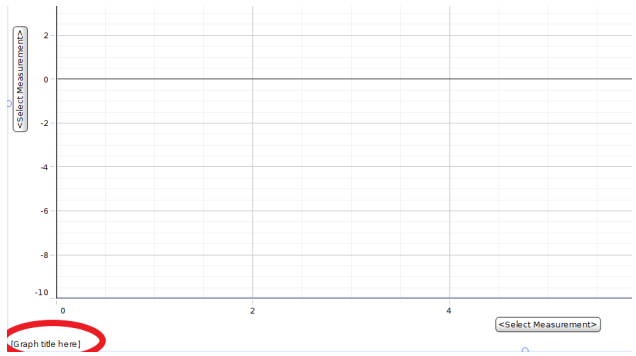


Figure 4. Always set a Title on your Graphs to help your reader.

(a) Autoscale data (b) Apply a Best Fit Line (c) Use Coordinates Tool (d) Add another set of data on the Y Axis

Figure 5. Various options at the top of a graph display.

- *Start the program and layout*: Double click on the little blue and white brick icon and the maximize the display to full screen. Around a mostly blank central white page on all for sides are your main control options. In order of use, start on the **left** with **hardware** configuration and **data parameters**; on the **right** select **display options**; on the **bottom** row buttons for **start/stop recordings** and related parameters. Finally, on the **top** icons are located for **data highlighting**,**analysis**, **fitting**, and **output printing and saving**. There is also an option or keeping a **journal** of the session for later printing or saving. All data can be saved or exported for safekeeping on flash-drives or importing into Excel.
- *Select and configure a sensor*: At the top on the left, the **hardware** button opens subscreens to select the sensor(s) of the day. Little **gear wheel** icons offer options for fine tuning.
- *Adjust significant digits*: Next down on the **left** is a **triangle rainbow** button where significant digits can be set up. Similar adjustments can be made elsewhere as well.
- *Analyze datasets*: Some of the **top** of the graph options allow to **highlight** (select) regions with the actual experiment data as defined earlier. Then you may perform statistics or fitting operations. On the graph you may pan and zoom to optimize the display as required for the lab notes and reports.
- *Prepare the display for printing*: On the very top list of tabs, **file** lets you set up the print format (must be landscape) and print graphs. Before printing, add labels. Several areas on the display allow for that. You may also drag a **textbox** onto the graph. This lets you correlate the printout with a location in your notes (and makes your grader happy).
- *Multiple measurements*: Capstone lets you take multiple runs. Just restart the recording and a new display starts. The older data are still present. A little rainbow triangle on the top bar lets you toggle through older **runs**.
- *Keeping a log*: Capstone offers the option to maintain a **Journal**. The button is at the top. It takes snapshots of the central display and maintains all in chronological order.

- *Record and saving activities*: Computer crashes and power outages happen. Note your findings in the lab notes. Print graphs. Save your data temporarily in the thaw-space on the computer's hard drive (or permanently on your flash-drive). Do not depend on the computer to keep your data. Crashes happen. You do not want to start all over.
- *What if the computer crashes?* Did you save your work and log it in your notes? No? **You just learned the hard way why you keep records on paper.** Restart the lab with.

Capstone and Excel data analysis

Capstone offers a large range of options to fit datasets on display in your graphs. It lets you select subsets of the full dataset and analyze them exclusively. Little boxes appear and show the results. Thin lines graphically represent the analysis outcome. Excel — originally developed to help with tasks in business — offers some additional capabilities for data analysis. Results from multiple measurement runs can be combined on spreadsheets to be graphed together as a function of your controlling parameters. Simple linear regression analysis can be performed on these results. More complex math can be performed on your columns of data. You may have some experience in using Excel. Some less common operations are covered here.

- *Graphs*: On the top bar of tabs go to **insert** and find **scatter**.
- *Axes labels*: Excel is not as convenient as Capstone for that. But, all the options are available.
- *Error bars*: Excel has powerful graphing options. You can add error bars to your graphs.
- *Linear regression*: This is the important one! **Do NOT use trendline.** On the top bar of tabs go to **data**. At the very right side under **Data analysis** a window pops up. Scroll down to look for **Regression**. This version will let you select x- and y-datasets, and fit a linear function. The results for intercept and slope will also carry an uncertainty. This is crucial. You must have uncertainties to finish your notes. Also, choose the options to display the results on a separate sheet to avoid overwriting existing data.
- *Record results*: Do not depend on Excel sheet print outs. Record the results in your lab notes. Annotate them so your grader understands what you did!
- *Graphs*: The same rules as for Capstone graphs apply. Excel requires more legwork to maintain units and suitable axes ranges.

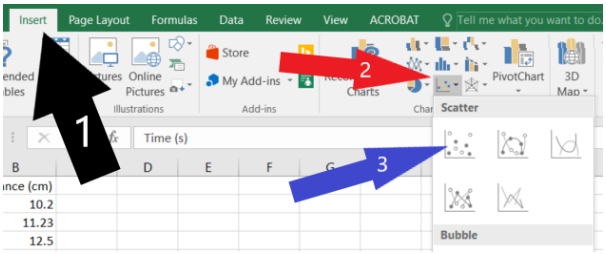
Microsoft Excel has quite a large suite of tools available for working with data. Since there are no prerequisite courses for this lab which have trained students to use Excel, experience levels will vary heavily. So the precise elements of Excel which will be required of students are based on what the Teaching Assistant desires to spend time teaching.

Whether by Excel or another program, you will need to produce graphs and perform calculations in the course. It is ideal to use whichever tools your Teaching Assistant is supporting, but in case you are incapable of making a graph in any other manner, this manual will present instructions for doing so in Excel.

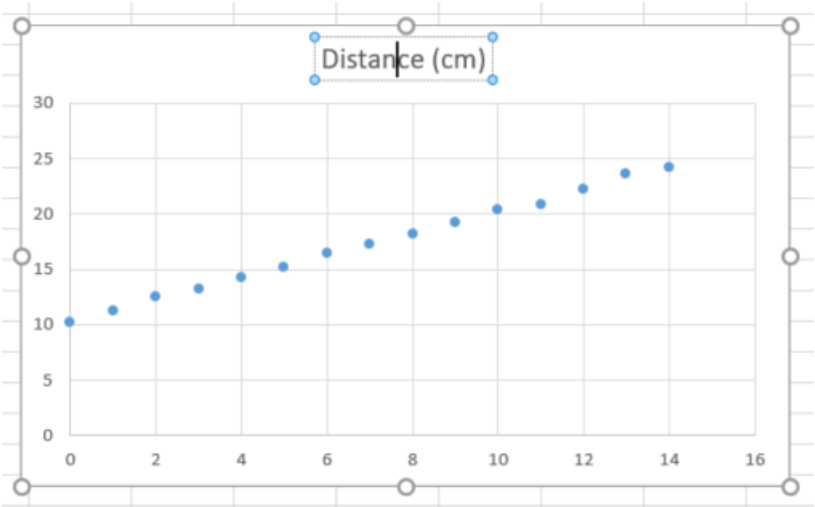
First, enter your data into Excel. Remember to take the time to place labels (including units) so you can make sense of the data at a later time.

	A	B
1	Time (s)	Distance (cm)
2	0	10.2
3	1	11.23
4	2	12.5
5	3	13.21
6	4	14.23
7	5	15.21
8	6	16.4
9	7	17.31
10	8	18.18
11	9	19.25
12	10	20.34
13	11	20.8
14	12	22.26
15	13	23.6
16	14	24.21

Now, select your data which you want to graph, and go to Insert->Scatter Plot.



Excel will place a title on your graph, often taking one of the labels from your data. This is rarely what you want the title to be, so change the title by double clicking on it. Then simply type in an appropriate title.



You should include labels for the axis in every graph so that a reader can understand the data without any other input. To add axis labels, click on the graph anywhere, and three options will show along the upper right of the graph area, click the + icon, and check the box for "Axis Titles"

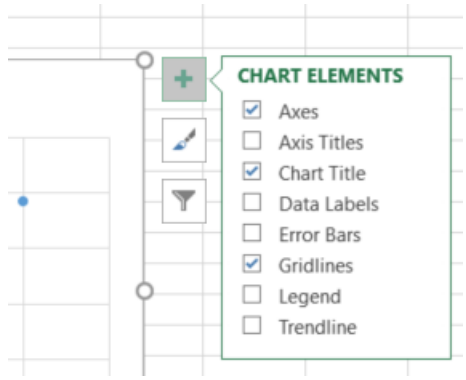
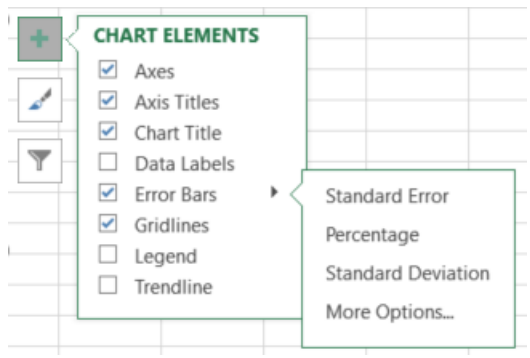
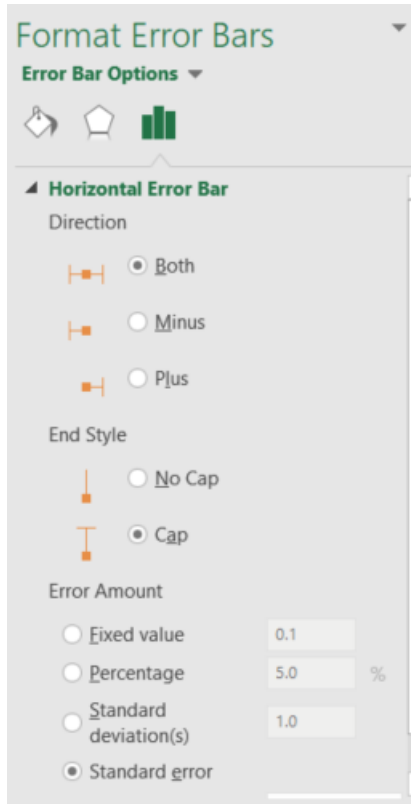


Figure 6. Enable Axis Labels, and then set the labels appropriately (include units!).

In that same menu area where you enabled Axis Titles, you can also enable Error Bars and Legend. Excel will automatically calculate Error bars using standard deviation, which is often acceptable but you can change the error bars if a different calculation is desired for the experiment. However, Excel will also add horizontal error bars, which are meaningless in most experiments, and so you need to hide those. If you expand the options next to Error Bars, you will be able to choose "More Options..."



By default, it opens up showing the options for the Horizontal Error Bars, which is what we want to eliminate. Enable the "Fixed Value" for Error Amount, and set the value to 0. Also select "No Cap" for End Style.



You should now have a graph which is acceptable for most data display requirements.

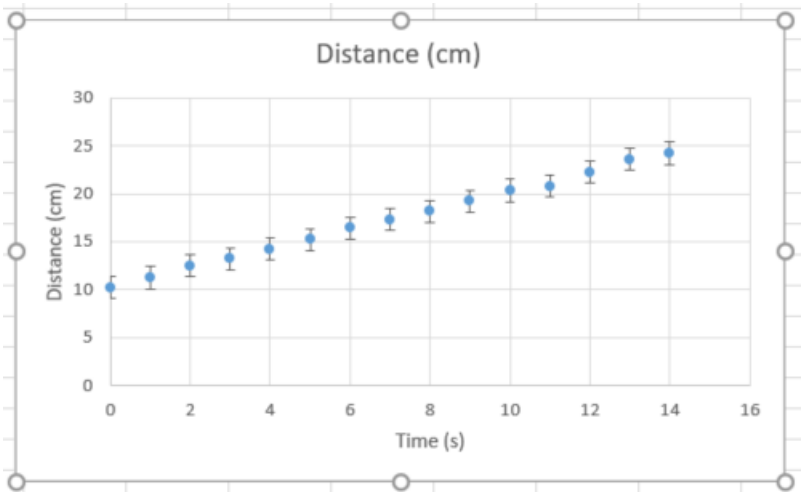
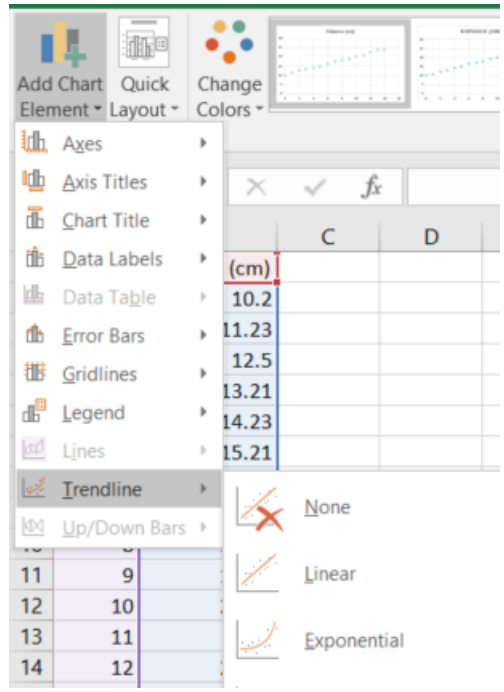


Figure 7. An acceptable graph for most display requirements.

In some cases you will also be required to include a best fit line. This is available from the "Add Chart Element" dropdown, under "Trendline." The choice of Linear or Exponential is typically all you need to know, and it is determined by knowing what kind of data you expected to be measuring.



If you double click on the Trendline, you can find an option to add the equation to your graph. This and adding a legend when graphing more than one data set can help improve your graph's ability to communicate information.

Page 130 contains further notes regarding Excel, and goes into detail which may be beyond what your teaching assistant requires for the semester if they have another software package they prefer to use.

Quantifiable tools to compare results: the t'-score

The end product of measurements and their analysis are a set of results. Quantitative results are values with uncertainty and units. For example, the acceleration of the basketball in free fall or the near lack of acceleration of a cart on a horizontal track. The final remaining task tends to be to bring these results into perspective. How do they compare to the initial predictions. The gravitational acceleration in Pullman is approximately $9.80 m/s^2$. Your result may be $g = 9.75 \pm 0.05 m/s^2$. Clearly the values are different. Should we contact the School of the Environment? The USGS? Unlikely. Chances are, their values are more precise. The equipment and methods here are not. So how can you judge, how reliable and trustworthy the results are? One way would be to look at the different datasets and extract how much they vary from run to run. From mathematics and thermodynamics it is known how to deal with statistical random fluctuations. That is the basis of quantifying the reliability and the underpinning of listing uncertainties. The uncertainty says that in 68 out of 100 cases a repeat of the experiment will result in a new value that is no more than one uncertainty away of the old value. In the above measurement of g the chance is 68% that the next measurement is gnext is within the range from 9.7 to $9.8 m/s^2$. Or, turned around, the chance of randomly measuring another value outside of this window is 32%. Double (triple) the window range and the chance drops to 5% (0.7%) of randomly measuring something outside the

range. If gnext were less than 9.6 or larger than $9.9 m/s^2$ this is a random outliner result in 7 out of 1000 measurements. The t'-score is simply the distance (absolute value of the difference) of one result (your lab result) from another result (or your prediction at the onset) Δ in comparison to the uncertainty u. The higher the t'-score the more likely something is different or the prediction was wrong or something unforeseen in the measurement deviates from the plan.[1]

$$t' = \frac{\Delta}{u(\Delta)} = \frac{\Delta}{\sqrt{u(m_{F/a})^2 + u(m_{bal})^2}} \tag{1}$$

The denominator is a tad more complicated. Typically, the result and the "compare to" values both have uncertainty. They must be combined. In statistics this is done in quadrature. Add the squares and then take the square root. In the labs here the critical value for t' is 3. If t' is smaller, there is agreement, if it is larger, something is different. In prize winning physics to convince the audience that something new was discovered or a theory proven wrong the t' must be larger than 5. The chance of a statistical effect drops below 1 in a million.

To analyze your data, you will constantly be using statistical analysis, sometimes beyond the *t'*-score. This branch of mathematics is unlikely to have been covered for any student previously, though it is of use to everyone at some point in their life.

In addition to the instructions from your teaching assistant, I urge all students to practice and refine their skills by using the resources available from Khan Academy.

There is a lengthy presentation about Uncertainty on page 111.

Summary

This is not an actual lab but more a tutorial of what to expect to encounter in the lab. Keep these instructions and guides in mind for your upcoming labs and note taking activities.

EXIT TICKET:

- ☐ Save what you would like to keep on a thumb drive or email it to yourself.
- ☐ Quit any programs you have been using.
- ☐ Straighten up your lab station, pick up any trash or personal belongings.
- ☐ Report any problems or suggest improvements to your TA.
- ☐ Record TA name and email address somewhere so you have it available through the semester.
- ☐ Have TA validate Exit Ticket Complete.

[1] N. T. Holmes and D. A. Bonn, "Quantitative comparisons to promote inquiry in the introductory physics lab," Phys. Teach. **53**(7), 352 (2015). DOI: 10.1119/1.4928350