Lab 0. Data Acquisition and Evaluation, a Tutorial

Goals

- To understand the purpose of experiments.
- To understand the key ingredients of experiments.
- To learn how to prepare lab-notes.
- To understand data acquisition with Capstone.
- To analyze data with Capstone and Excel.
- To compare results and predictions.

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Important Notes

- Read the lab manual syllabus. The manual is available online at http://www.physics.wsu.edu.
- Read the lab manual experiment section before the actual lab session. Time is not plentiful. You can save a lot of time by preparing.
- There are sections in the back of the lab manual covering the use of Capstone, Excel, Data uncertainties, and the calculation of the t'-score as a means to compare results from different sources.
- If there are questions, concerns, or problems with the lab session, feel free to contact the lab director. His contact information is listed at the beginning of the lab manual. The e-mail contact is physics.labs@wsu.edu.

Experiments in Physics

> “An experiment is a question which science poses to Nature, and a measurement is the recording of Nature’s answer.” Max Planck

Radiation is present everywhere. Many natural and manmade sources exist. Here, radioactive sources are used to observe effects of distance from the detector.

Experiments are a method to check and verify or disqualify these generalizations. They are used to probe the limits of generalization. Experiments are also meant to be reproducible. Given sufficient information, anybody should be able to repeat the experiment and observe the same results.

Ingredients of experiments

An experiment is basically a series of answers to a list of questions. In the undergraduate labs a number of them are either covered in the lecture or pre-configured in the laboratory:

- ***What do you want to know?***
- *What do you know about this?*
- *How to simplify the problem as much as possible?*
- ***What will happen?***
- *How much time is available?*
- ***What’s the plan?***
- ***Execute the plan***
- textbf*Analyze the data*
- ***Compare to prediction***
- *Draw conclusions*
- *What can/should be done in further experiments?*

“What do you want to know?" A radioactive source emits radiation into all directions equally. Geiger counters are used to detect the rate at any position. How does the rate decay with distance? No lecture has covered this. But some general thoughts can be compiled how the radiation spreads out from a point into space. These ideas are **known** components. Gamma rays are not the only versions of radiation. Sun-light or light from LEDs and light bulbs are other sources.

To **simplify** the situation a radioactive gamma ray source is picked. This eliminates the need to consider multiple sources and reflections of visible light.

Predictions regarding it’s charge retention can be made. Your TA will discuss this.

Each lab lasts just under 3 hours. The teaching assistant will give some instructions at the onset. Then, about 2.5 hours are left. It is useful to **manage the available time**. Each lab experiment consists of several mini-experiments or runs. Each run may take a minute. For example, sets of about 5 runs are to be carried out each for a number of different starting parameters. 5 runs of 1 minute each for 5 different parameters result in 25 minutes. After 15 to 20 minutes of an introduction that leaves the experimenters nearly 2 hours to analyze data and record the activities and results.

The **plan for the experiment** is established in the lab manual as well as the introduction by the teaching assistant. However, at times planning may be left to the experimenters. The equipment is installed, sensors are selected and mounted. What remains is to initialize the sensors and data acquisition and to execute the plan.

Typically users are left to **execution of the plan** and to **analyze the data**, i.e. to finalizing the experimental setup, collect data and to extract results from an **analysis**.

Finally, the results are **compared to predictions** or previously existing data. Based on the comparisons conclusions are drawn to either confirm the original hypothesis and predictions. Or, they have to be augmented or even discarded.

Lab-notes

A big component of the power of science in general and physics in particular is the emphasis on reproducibility. One can perform a calculation or an experiment over and over and obtain the same result. For that it is crucial to understand how to compare results, a topic that will be covered further down. The other component are detailed and precise notes.

Lab notes and lab notebooks are legal documents. They are used in patent cases and ownership disputes. Nobel prizes and honors are handed out based on records from lab notes. Important findings are witnessed and countersigned and dated. In undergraduate labs this is practiced to get the hang of it.

While conducting the experiments, the lab-notes are a running log of all activities undertaken in chronological order. They commence with the objective of the experiment at hand. They include the setup of the experiment, the recorded data and the methods of analysis and the results. These notes may be cryptic and a form of short-hand for the experimenter. A more formal report is more like a communication with the community that includes more details and combines data from series of related experiments. The formal notes tend to omit deviations or dead ends in order to streamline the notes. They also include more on the background and motivation for the experiments. Details of a formal lab report are discussed elsewhere.

Providing some structure in lab notes is useful not only for grading but also when it comes to their use as a memory aide. This is tested during the final lab exam. Items that are required for lab notes and make them easy to use include:

- *A cover page*: 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. Note if this is a makeup lab.

- *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.

- *An introduction*: This part should include the objective of the experiment. All relevant physics, such as equations should be included here. They may come from the lecture material and textbooks as well as information from the teaching assistant. A bullet list may be advisable.

- *The setup and sketches*: A description of the experimental setup. Following the proverb "A picture is worth a thousand words." Sketches, free-body diagrams and drawings are worth more. Sketches are not images or photographs. They leave out all but the essential parts. For example, the position of a sensor is more important than the actual shape. If a line is meant to be straight, add a note. The orientation of the source may matter. One side has thicker plastic which may alter the emitted intensity.
- *Commentary for math*: Don't just write down equations. Annotate the equations, very much like you expect from a textbook.
- *Run configuration*: For each mini-experiment or run, one or at times more parameters may be changed. Note the changes. One may want to label the data-set or resulting printout accordingly for easier identification.
- *Taking data*: Besides rates and distance, one may note down how long the measurement was carried out for. The orientation of the source was already covered. Other materials such as lead behind the source may matter.
- *The actual experiment*: Not all of the collected data 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**.
- *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.
- *Printouts*: must be labeled. One may note in the lab notes to refer to printout number 5 at this location. Tables of analyzed results for example from Excel should be printed out.
- *Graphs of data*: Make them **big**. Full page landscape is essential for full credit. Maximize the view of the data such that possibly important trends are in plain sight.
- *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 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*: Fits will be made to find best matches of functions with datasets. Again, highlighting the region that is the basis for a fit. Results should also be in the lab notes and not just on the graph.

- *Results*: Record the results. Draw a box around them, to highlight. Be mindful of significant digits. Digits beyond the uncertainty are irrelevant and add confusion. Every result has a value, an uncertainty and units. The measurement records number of counts (detected gamma ray photons) in a set amount of time. Fractional counts only exist when computing rates or counts per time. If 100 seconds was the measurement time, there is no reason to note more than 0.01 counts per second precision. Likely, even that precision is unrealistic, depending on the source.

- *Summary and conclusions*: Statements like "we measured a lot" summarize nothing. A summary pulls together key results and findings that answer the initial question. Statements like: "With distance the radiation rates drop as a function of distance r in a power law dependence" compile the findings of an experiment and provide useful information to a reader. The determined power value and uncertainties should be listed.

Other practices are useful, help when the notes function as memory aides and make grading easier, i.e. result in higher scores.

- *Be brief*: These are not novels. Lab-note are memory aides for you (and the exam) and recipes and procedures to reproduce the experiment.

- *Do not leave blank space to fill in later*: These are chronological notes.

- *Mistakes* are simply crossed out. Add a reference to where the corrected or updated information is found. There, add why the change was made.

- *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.

To understand data acquisition with Capstone

The program Capstone is used to control a variety of sensors used in the coming labs. It is of great advantage to master essential parts of the program's capabilities. A separate more detailed file will be available online during the labs. An overview of them will be given in order to:

- *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 sub-screens 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.

- *Set up display options*: On the **right** click, hold and drag your choices for display onto the central page. There are graphs, tables, histograms, and more to choose from. Details depend on the requirements of the lab. Up front, simple graphs will do. The axes labels are buttons where you can choose what to display as the x- and y-axis values. Starting with the y-axis automatically sets the x-axis to time in seconds. Buttons at the top of each graph or table appear when clicking on a graph. These let you manipulate the display or add further graphs.
- *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.

To analyze data with Capstone and Excel

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.

- *Math*: Excel lets you do all kinds of math on any worksheet item or column. Each little box has a column character (A, B, C, ...) and row (1, 2, 3, ...). Click on a box where you want a calculation done and then start typing "$= 3 * B5 + D2$" to multiply the value in box "B5" with 3 and add the value of box "D2". Clicking on the box, will give it a fat black outline with a small separate dot in the lower right corner. Clicking on that dot and dragging the mouse down over multiple boxes will apply the same math to all the new boxes. The “B5" and “D2" box addresses will also move along. This can be prevented by changing “B5" to “B5" for example. Now the same value will be used.

- *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.

For many users Capstone as well as Excel are big mysterious programs. They are very powerful and hence the learning curve may be steep. Hang in there. Most tasks in these labs are relatively simple. Learning how to calculate functions in Excel rapidly leads to lots of time saved. Using Excel reduces the chance for errors and makes it possible to find and fix errors that do occur.

To compare results and predictions

In many cases the experiment is to demonstrate that a concept introduced in class is true and applies at least in the lab, if not in the real world where more out of control variables are at play. Coming back to the radiation sources, the expected rate versus distance decays inversely with the square of distance. Experimental results may differ for a number of reasons including the presence of shielding obstacles such a lead or water.

Is a prediction made early on proven wrong? Is the difference to the prediction of zero significant? The comparison or ratio of this difference to the uncertainty offers a clear cut and reproducible method of deciding.

The difference of a measurement m to a prediction p of a theorist or the measurement of a competitor is Δ:

$$\Delta = |m - p| \tag{1}$$

This is then compared to the uncertainty of the measurement m called $u(m)$ combined with the uncertainty of the prediction p called $u(p)$. From mathematics and statistics it is known that the combined uncertainty $u(\Delta)$ is by adding in quadrature:

$$u(\Delta) = \sqrt{u(m)^2 + u(p)^2} \tag{2}$$

The ratio of these is called the t'-score.

$$t' = \frac{\Delta}{u(\Delta)} = \frac{\Delta}{\sqrt{u(m_{F/a})^2 + u(m_{bal})^2}} \tag{3}$$

Nominator and denominator have the same units (from the measurement). Consequently the t'-score has no units. It is also always positive. The higher the t'-score is, the more likely the compared values are not in agreement. In the undergraduate laboratories the cut off value is $t' > 3$ for m and p being different and $t' < 3$ for them to be in agreement. In the latter case, if p is the prediction, then the prediction is confirmed by the experiment.

In modern groundbreaking experiments where standing theories are overturned, a t'-score of more than 5 or even 7 is essential to convince the community of physicists.

The nature of how uncertainties are evaluated based on statistics make it harder and harder to reduce the value of the combined uncertainty in order to drive up t' for a given difference. In general the uncertainty $u(m)$ says that in 68 out of 100 repeats of an experiment the result of any two will agree within $t' < 1$. A $t' > 2$ says that in 5 of 100 cases there is agreement. 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]

[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

Let's try this out

#	Task or Activity	Labnotes	Data	Results
1	Start			
		Heading and date/time	Name, TA, class, section	
	What do you want to know?			
		Radioactivity (cart) at any distance		
	What is known?			
		distance $= x$	rate(s) equations	
2	Setup			
		sketch, configuration	set parameters	
3	Predict			
		rate vs time	hand graph	shape of line(s)
4	Finish setup			
		distance connect sensor	counts	
5	Execute			
		Start record	table of x and rate	
6	Analyze			
			Capstone: fit vs. distance x	
		Excel: average		
			from regression	
7	Compare			
		predicted: inverse x^2 data	$t' = \frac{\Delta m}{u_{combined}}$	agree or not
8	Conclusions			
				acceleration (?)

You will work through this table with your teaching assistant during this tutorial. In the following labs, you will be left to do more on this by yourself.

Summary

This is not an actual lab but more a tutorial of what to expect to encounter in the lab. Together with the teaching assistant an experiment was carried out. The experiment was preconfigured and set up. Data were acquired and analyzed, the resulting values for acceleration were compared to the prediction of zero acceleration. It was found that the prediction was .... (to be continued).

Keep these instructions and guides in mind for your upcoming labs and note taking activities.

Before you leave the lab please: Save what you would like to keep on a thumb drive. Quit Capstone and straighten up your lab station.