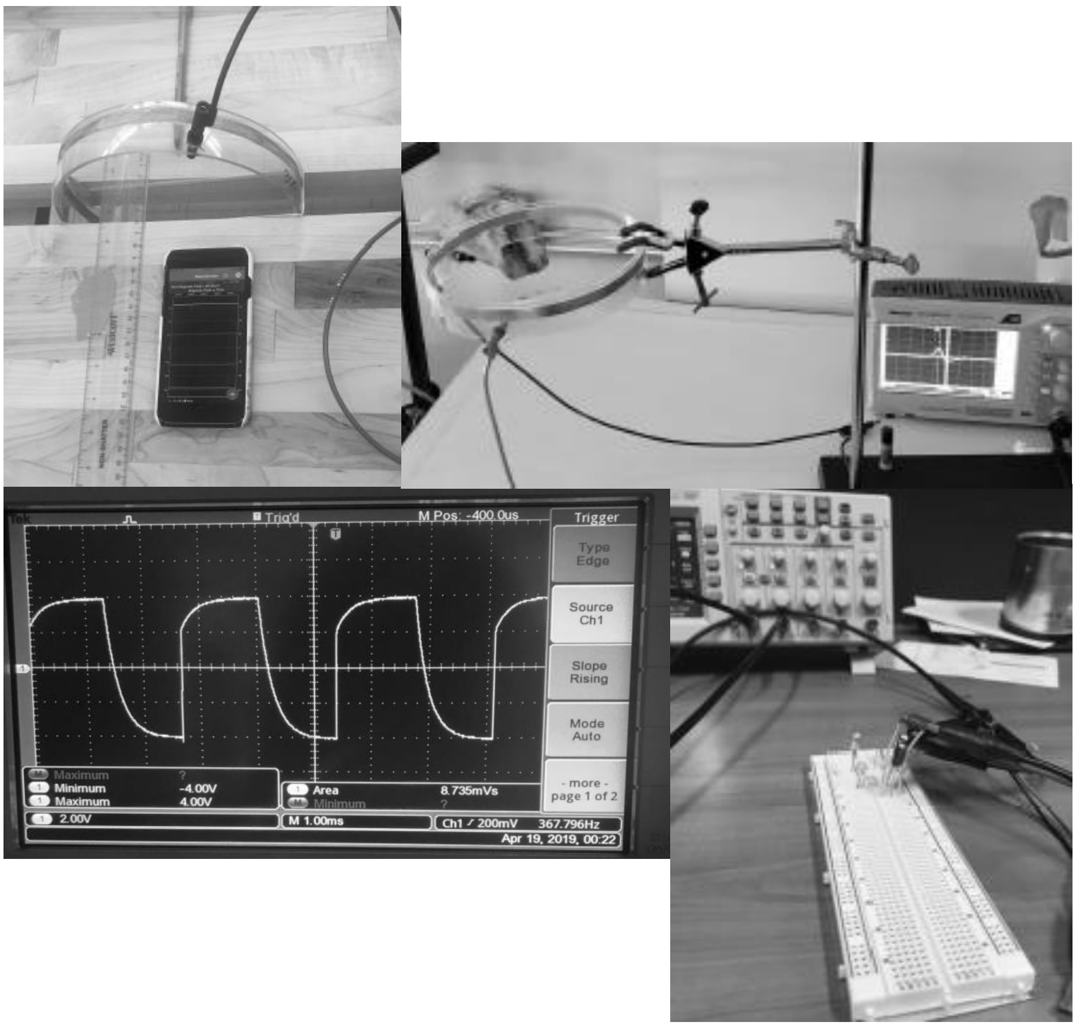
PHYS 2217
LABORATORY MANUAL



SPRING 2020

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Edited (Spring 2020):

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Welcome to the 2217 lab!

This lab is intended to be an introduction to experimental physics in the context of electricity and magnetism. The lab aims to teach critical thinking through experimentation: **how do we know what to trust and what to do?** The objectives for this course fall under five big themes:

Lab Objectives:

By the end of this course, students should be able to:

1. Collect data and revise an experimental procedure iteratively and reflectively,
2. Evaluate the process and outcomes of an experiment quantitatively and qualitatively,
3. Extend the scope of an investigation whether or not results come out as expected,
4. Communicate the process and outcomes of an experiment, and
5. Conduct an experiment collaboratively and ethically.

The full list of specific learning goals is available on Page 49. Each unit lists the specific learning goal being targeted. Each experiment will focus on developing and applying tools of experimental physics to extend our understanding of physics principles. Experiments will often aim to build models to represent specific physical situations.

The goal is to understand *how* we know, not *what* we know.

The E&M lab will focus on what we call "model building," that is, using experiments to **build models** that represent, explain, and predict E&M phenomena.

Often, material or experiments discussed in lab will take place *before* you have discussed the relevant topics in lecture. In some cases, the material will never be discussed in lecture.
This is deliberate.

In many situations, experimentalists do not know what results they are going to obtain and they may simply discover something "by chance." Only after doing the experiment do they engage in the process of trying to understand the phenomenon, based on the experimental data they have collected. This process can be contrasted with "model testing," where an experimentalist has a proposed or hypothesized model in mind, and is conducting experiments to test its robustness, to see if or when or where it breaks down, or to see if there is evidence of new physics hidden somewhere.

What will I do in and out of lab?

Most lab work will take place during the lab period, except for short, individual Post-Lab activities. All materials will be submitted through Canvas. Most lab units will be split across two sessions, with the typical activities as follows:

Session 1	
Before:	• Read over the lab instructions.
During:	• Familiarize yourself with the equipment and physical system and evaluate a given research question. • Answer questions in the lab handout. • Formally check-in with your lab instructor. • Submit your lab notes (by the end of the session).
After:	• Complete and submit the Session 1 post-lab activity by 5 pm TWO DAYS before your next lab session.
Session 2	
During:	• Conduct a more independent investigation that builds from and extends the methods and results from the first session. • Answer questions in the lab handout. • Formally check-in with your lab instructor. • Submit your lab notes (by the end of the session).
After:	• Complete and submit the Session 2 post-lab activity by 5 pm TWO DAYS before your next lab session.

How will I be graded?

Each lab session will be worth ten points total split as follows:

Lab notes – 5 points: By the end of each lab session, your group will submit your lab notes that document what you did during lab and why you did it (one set of notes for the whole group). These will be graded according to the rubrics provided on page 27.

Participation – 2 points: During each lab session, your lab instructor will check in with you regularly to evaluate your participation and your group's progress, experiment planning and design, analysis, and overall teamwork.

Post-lab activity – 3 points: Each lab session has a corresponding post-lab activity with questions that ask you to reflect on the lab, plan for the next session, or practice the ideas introduced in lab. The post-lab activities will be graded based on effort and correctness.

What goes in my lab notes?

During each lab, you will document your group's decisions, data, and analysis in an electronic lab notebook **as you work in the lab** and submit them by the end of the lab period. Lab notebooks are regularly used in experimental work and document the details of an investigation. Scientists and engineers use lab notebooks as records of their activities with a project. Often, lab notebooks are the property of the lab, not the individual, and get passed down from person to person. A scientist or engineer may refer back to the lab notes between days in the lab to pick up where they left off, when writing a more formal manuscript to recall why they conducted the experiment a particular way, or when working on a similar project to help troubleshoot a problem they may have already solved. For work that may result in a patent or contentious 'who did it first' debate, each notebook entry is time stamped and pages are never removed from the book. **Lab notes should NEVER be deleted or erased** – only added to and extended. Learning how to keep and use a lab notebook are explicit learning goals (Goal: 4.a i, ii and b).

Practically speaking, think of your lab notes as a stream of consciousness. They should be quick notes that document what you were doing and why you were doing it at several time points throughout the lab. **Lab notes are NOT a formal report.** They do not need to be in full sentences. They can be bullet points. They should not take up a lot of time. **You should try to update them throughout the lab – don't leave it to the end!**

Your lab notes should always include (at minimum) the following: the date; the name of the person making each entry; descriptions and justifications of methods; collected data; analysis and calculations; descriptions and justifications of changes made throughout the process; reflections and conclusions. Data and analyses can be submitted through spreadsheets and do not need to be duplicated in the text.

Group Members: ___________________________ Group Name: _____________

Unit 0: Intro to Model Building

Learning goals:

By the end of this unit, you should be able to:

- Describe how we come to know things and build models in physics, and relate it to the course learning objectives and goals.

Activity I: What is experimental physics?

In your group, get a whiteboard, a few whiteboard markers (at least one per person), and an eraser. **Your instructor will ask you a question** – on your whiteboard, generate a presentable answer to the question. You will be asked to present your ideas to the class.

At the end of the discussion, have at least one group member add a picture of your group's whiteboard to their Canvas page and make sure all group members can access it. This should help you get familiar with how to share submission materials on Canvas.

Activity II: Submitting on Canvas

Spend some time exploring the Canvas Modules on your computer. After you have spent some time exploring, work with your group to answer the questions in the box below.

1. Where can you find the questions for the first post-lab assignment?

   ____

2. Where will you submit the first post-lab assignment? ___________________________

3. When is the first post-lab assignment due? ___________________________________
4. Sign yourself up in a Unit 0 group on Canvas with your lab partner(s). Use only existing groups listed for your section (do not create your own group).

   What is your Unit 0 group name? ____

5. How can you create and view lab notes shared between your group members?

   ____
6. Add a picture of your group's whiteboard to shared **lab notes online** and make sure all group members can access it. Submit as an assignment to Unit 0 Lab Notes.

Unit 0 – Post-lab

1. In the introduction to the lab, we defined critical thinking in experimentation related to how we know what to trust and what to do. Drawing on the "How do we build models of the physical world?" activity from lab, answer the following questions:
    a. How can we know if experimental results, data, or models are acceptable or trustworthy?
    b. How do we do experiments in physics?
    c. How do we work together to solve a research problem?

2. This exercise aims to remind you or familiarize you with some of the quantitative analysis tools that will be used in this course. **Please refer to the Statistics Summary on Page 31 for guidance.** These questions refer to the data in the table, which we will assume were collected previously from an experiment where the expectation was that the relationship between x and y was linear.
    a. Use the manual fitting template on Canvas and **the Statistics Summary on Page 31** to test the degree to which the data fit the model: y = 10x.
        i. Calculate the weighted χ^2 value for the fit.
        ii. Interpret the value of the weighted χ^2 and comment on the quality of the fit from the graph of x vs y and the residuals graph.
    b. Use the automatic excel fitting template on Canvas to determine the best-fitting linear function to the data.
        i. Report the best fitting model.
        ii. Calculate the weighted χ^2 value for the model.
        iii. Interpret the value of the weighted χ^2 and comment on the quality of the fit from the graph of x vs y and the residuals graph.
    c. Given that the researchers expected the data to fit a straight-line model, what are three reasonable things the researchers could do next? Justify your suggestions from the analyses in the previous questions.

x	y	Uncertainty in y
1	10	1
2	19	3
3	30	4
4	48	10
5	66	10
6	84	4
7	113	3
8	141	1
9	182	7

Group name: _____________ Group members: 1.____________2.____________

Unit 1: Model Building

Learning goals:

By the end of this unit, you should be able to:

- Propose testable models to explain observations, and use the models and observations to make predictions about a new experiment [Goal: 1.c) i, iv, 3.b) i-v, 3.c) i, ii].
- Evaluate whether results agree with predictions, and design further tests if the results agree or modify and test explanatory models if the results disagree [Goal: 3.a), 3.b) i-v, 3.c) i,ii)].
- Keep record of all decisions, data, and interpretations in digital lab notes [Goal: 4.a].
- Motivate all research questions, conclusions, claims, and interpretations with supporting data [Goal: 3.a), 4.d)].
- Work collaboratively with other group members (i.e., listen to everyone's ideas, rotate roles, allow others to lead, share responsibilities) [Goal: 5.a), 5.b), 5.c)].

Activity I: Modeling electrostatics

Your instructor will show your group a demonstration to kick off today's investigation.

A. Develop a model

After the demonstration, brainstorm with your group to develop **several testable** models that could explain the demonstration. Document as many ideas as you can come up with in the box. These need not be *plausible* models: It is just as important, if not more important, to rule out models as it is to provide evidence in support of a model.

Possible testable models

In your **lab notes online**, record at least two of the models you came up with and describe how you would test the model and what you would observe if the model holds or does not hold.

For each model, carry out your experiment and carefully document the outcomes in your **lab notes online**. Does the evidence support or refute the model?

- If all your models are refuted, modify your models or develop a new model based on the evidence that you have gathered and design a new experiment to test this new (or modified) model.
- If one (or more!) of your models are supported by evidence, design and conduct additional tests that will probe the limits of the model(s).

Initial model(s) was/were: **supported / refuted (circle)** **Summary of follow-up investigation and justification:**

Record your process and observations in your **lab notes online**. Continue this process until you have ample evidence to support one (or more!) model.

Reminder: In science, we can show that an explanation is supported or refuted, but we cannot show that it is true.

B. Test your model in new contexts

After you have a well-supported model, visit a neighboring group. Observe their demonstration and record whether their evidence supports or refutes your working model. As before, if your model is refuted, modify your model and/or design and carry out additional experiments to test this model. If your model is supported, design and conduct additional tests that will probe the limits of the model(s).

Visit several groups and repeat this process with as many of the demonstrations as you have time to fully investigate. You may also extend individual demonstrations to test additional variables. **Fully document your process in your lab notes**.

Towards the end of lab, groups will briefly report out on their investigations.

Supplemental Information: Group Roles

Throughout this activity, your instructor will assign and rotate group roles. Regardless of the assigned role, each group member should participate in shared responsibilities such as contributing ideas, using experimental equipment, and making decisions.

Principal Investigator (PI): The PI makes sure everyone has something to be working on that contributes to the progress of the group. The PI establishes an environment where all group members are comfortable with and encouraged to share their ideas and contribute to the collaboration. The PI facilitates discussion to resolve disagreements and can decide if no group consensus is reached. The PI constantly pushes the team forward at a fast pace but also encourages quality research decisions and effective collaboration.

Reviewer #2: Reviewer #2 constantly takes a step back to critically look at the experiment design or execution and suggest areas for improvement. Reviewer #2 is responsible for questioning all decisions to make sure that ethical and rigorous research practices are in place at every step of the investigation. Often this role slows down the progress of the group due to the skepticism required.

Science Communicator: The Science Communicator is responsible for making sure the group's progress is documented and justified. Collaborators within AND scientists outside the group should be able to understand exactly what has been done and why it was done, so the Science Communicator needs to keep an outside perspective in mind when contributing to decisions within the group. If results need to be presented to the public or other scientists (i.e., your classmates in lab), the Science Communicator coordinates this process. <u>Note: they do not need to be the ones writing or presenting – they are just responsible for making sure what is written and presented is understandable to people within and outside the collaboration. Anyone within the group may be recording or presenting, regardless of their assigned role.</u>

Unit 1 – Post-lab

1. You and two friends are having a debate about objectivity in science. One friend argues that science is always objective by nature. Your other friend argues that the fact that science is done by humans means it is always subjective. With whom do you agree more? Explain your reasoning.
2. We used the term "model" several times in Unit 1. Answer the following questions by using specific examples from lecture, lab, other classes, or your own experiences.
    a. What is a scientific model?
    b. What is the role of a model in an experiment?
3. Reflect on what you found experimentally last lab.
    a. What conclusions did you draw about models that explained your data?
    b. For one of your models, describe how you tested it and what you found.
        i. When was the model appropriate? How did you know?
        ii. When was the model inappropriate? How did you know?
        iii. How did you improve your measurements or your model?
        iv. If you had more time, what would you want to investigate next?

Group name: ____________ Group members: 1.___________2.___________

Unit 2: Model Building and Testing

Learning goals:

By the end of this unit, you should be able to:

- Use proposed models to make predictions and justify experimental design decisions such as how much data to collect and how to space data collection [Goal: 1.d) i,iii].
- Manage time by conducting pilot experiments and plotting as you go [Goal: 2. f)].
- Troubleshoot circuit by systematically isolating and testing different components (not "trial and error") [Goal: 3.b) iii].
- Linearize data via semi-log and log-log plots and use linear least-squares fitting on the linearized data [Goal: 2.e) i-v].

Activity I: Familiarizing yourself with equipment

This first activity aims to familiarize you with equipment that will allow you to design and carry out experiments with circuits, namely oscilloscopes, DC power supplies, and function generators. There are instructions **at the end of this unit** for tips on viewing and measuring the signal. Check in with other groups if you need additional assistance with the set up. If you quickly set up your oscilloscope, *assist groups that are still in the process*.

A. DC power supply

Connect the ground on the oscilloscope (black terminal) to the ground on the DC power supply (black terminal) and then connect the "positive terminals" (red) together. Press "Autoset" on the oscilloscope.

a) What do you initially observe on the oscilloscope (assuming everything is on)?

b) How does changing settings on the DC power supply affect what you see on the oscilloscope?

c) How can you "zoom-in" to view part of the signal in greater detail?

d) What happens if you connect the ground on the oscilloscope (black terminal) to the positive terminal (red) on the DC power supply instead of to the ground?

B. Function generator

Connect the ground on the oscilloscope (black terminal) to the ground on the function generator (black terminal) and then connect the "positive terminals" (red) together. Set the function generator to produce a 100 Hz square-wave source. Press "Autoset" on the oscilloscope.

a) What do you initially observe on the oscilloscope?

b) How does changing settings on the function generator affect what you see on the oscilloscope?

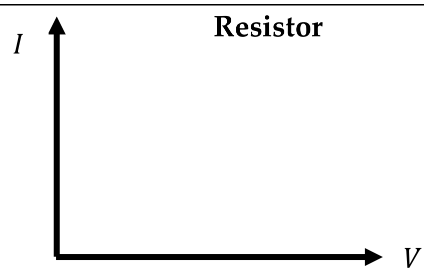
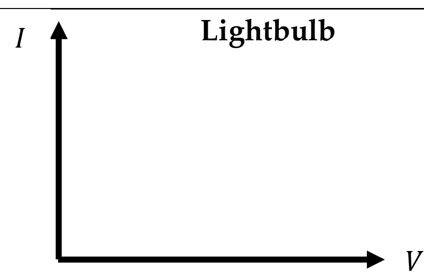
c) What happens if you connect the ground on the oscilloscope (black terminal) to the positive terminal (red) on the function generator instead of to the ground?

Activity II: Testing the V=IR model

A simple model used to describe simple circuits relates voltage difference ΔV, current I, and resistance R: $\Delta V = IR$. We'll test the model for resistors or lightbulbs by collecting data and plotting I-V curves.

A. Predictions

Sketch your predictions on the axes and explain your reasoning in the boxes, including any assumptions or approximations you make.

Resistor 	Why?
Lightbulb 	Why?

B. Test the model with resistors

Set up a simple circuit to measure the voltage across and the current through a resistor connected to a DC power supply.

Draw your circuit diagram, including how to measure the current and the voltage using the digital multimeters (DMM) and the oscilloscope. See the FAQ on page 13 for symbols to use.

Build your circuit and check it with your TA before turning anything on.

Work with your group to design your experiment, considering the following:

1. How will you analyze whether your data are consistent with the model?

2. What are your dominant sources of uncertainty? How will you characterize and quantify those sources?

Document your experimental design in your **lab notes online**. Conduct your investigation and document your results and any changes to your methods in your lab notes online. Be prepared to share your investigation with the class.

NOTE: Do not draw current greater than 20mA through your circuit components. If your experiment requires greater than 20mA, then first discuss your plan with your instructor.

C. Test the model with light bulbs

After exploring resistors, design an investigation to test the behavior of light bulbs.

Use your observations and results, as well as those of other groups, to develop and refine a model for the electricity through a light bulb. Justify each model that you develop from your data by performing statistical tests, using the model to make a prediction about a new result, and identifying limitations to the model.

Providing convincing evidence that data is inconsistent with a possible model is equally as important (if not more so) as providing convincing evidence that the data is consistent with a model.

D. Extend your investigation

For the remainder of lab, design new experiments to extend your models, test the limits of your models, or explore the applicability of your models to other materials, such as LEDs. Push your investigation to learn something new, either about the relationship between voltage and current or about your circuit components.

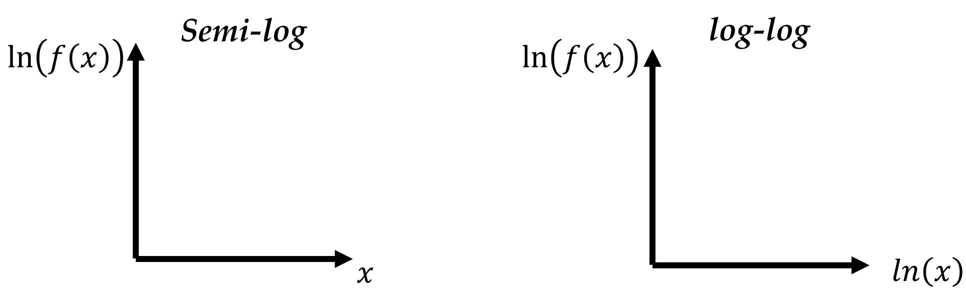
REMINDER: Do not draw current greater than 20mA through your circuit components. If your experiment requires greater than 20mA, then first discuss your plan with your instructor.

Activity IV: Linearization

In previous labs, we've plotted functions that we expect to be straight lines. What if we don't know the type of relationship we'll be obtaining? We're going to consider two families of relationships: *power laws* and *exponentials*. A power law is one where the variable is at the base and raised to a power, while an exponential has the variable in the exponent. That is:

Power law: $f(x) = Ax^B$ Exponential: $f(x) = Ae^{Bx}$

where A and B are constants. Our trick is to create two types of plots using the natural logarithm: semi-log and log-log plots, as below:

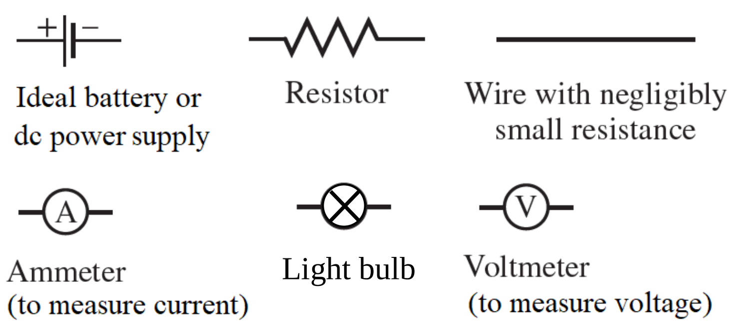


In your group, use your whiteboard to work through why these two types of graphs are useful for distinguishing power law from exponential relationships.

If we were to use linear least-squares fitting to evaluate the quality of the relationships, how would the slope and intercept in each case relate to the constants A and B from above?

FAQ: Circuit Set Up

1. *How do I measure current?* Digital multimeters (DMM) and the power source both measure current. To use the DMM, place the DMM in series in your circuit using COM and a terminal to measure current. The power source produces direct current (DC). Use the dial to set the DMM to measure current according to the scale and precision of your system. **Do not exceed 200mA if using the “mA” terminal on the DMM.**
2. *How do I measure voltage differences?* The DMM also measures voltage differences, using a different setting on the dial. Voltage differences are measured across (in parallel with) the circuit element of interest. Usually it’s easiest to begin by setting up and testing that the circuit works and then adding the multimeters.
3. *What symbols do I use in a circuit diagram?* There are several standard symbols for drawing circuit diagrams:



1. *What is this thing showing me?* The grid on the oscilloscope shows voltage in the vertical direction and time in the horizontal direction.
2. *How do I change the scale?* Use the "Scale" knobs! There are separate ones for changing the vertical (voltage) and horizontal (time) axes. You can also adjust the position of the signal with the "Position" knobs. The separation between the major grid lines is given on the bottom in the colors corresponding to each channel. These are good things to keep note of in your lab notes!
3. *I can't see anything or I'm not seeing what I expected. What do I do?* Here are some things to try*:*
   a. Press "Autoset".
   b. You may not have it set to display the channel you want. Turn on channel 1 by pressing the yellow "1" button (figure out what Channel 1 is measuring and note in your lab notes!), and you might need to change "Probe 10x Voltage" (multiplies your measured voltage by a factor of 10) to "Attenuation 1x".
   c. *Still no?* Repeat the previous step for Channel 2.
   d. *Can we see the function generator?* Hook up the oscilloscope to read the voltage difference across the function generator terminals using Channel 2 (make sure grounds are connected). Is that what you expect? If not, there may be something wrong with your circuit.
4. *How do I measure voltage differences with an oscilloscope?*
   a. Press "Cursor" and select "Type None". From the list, use the Multipurpose knob to select "Amplitude" ("Time" will allow you to simultaneously measure differences in time and voltage).
   b. Adjust "Source" to the channel that you wish to measure.
   c. Use "Cursor 1" and "Cursor 2" to measure differences in voltage and time between the two cursors.

Unit 2 – Session 1 Post-lab

1. Reflect on your process and findings from last week:
    a. What did you do and what did you find?
    b. What was surprising about your investigation?
    c. What do you want to pursue next time?
2. During lab you have been introduced to the roles of Principal Investigator, Reviewer #2, and Science Communicator. Reflect on your experiences acting as and interacting with each of the roles during lab.
    a. Which roles were easy to assume? Which were difficult to assume? Why?
    b. Which of other people's roles were easy and which difficult to interact with? Why? How did the interactions change depending on your role?
    c. When conducting research, in what ways may you take on <u>each of the roles</u>?
    d. What other roles do scientists assume as they conduct research?
    e. How do these roles contribute to ethical and responsible research practices?

Unit 2 – Session 2 Post-lab

1. This exercise is intended to help you practice linearization techniques. In the table are measurements of some quantities x and y, with uncertainties in y, dy.
    a. Generate three graphs to qualitatively check whether x and y are related linearly (plot x vs y), exponentially (plot x vs $\ln(y)$), or according to a power law (plot $\ln(x)$ vs $\ln(y)$).
    b. Based on your graphs, draw a preliminary conclusion for the relationship between x and y. Use your graphs to estimate any relevant constants.
    c. Summarize, in your own words, why log-log and semi-log linearization is helpful for identifying non-linear relationships.

x	y	dy
1	3	2
2	9	4
3	21	2
4	33	4
5	50	2
6	77	4
7	103	2
8	130	4
9	166	2
10	205	4

2. Consider your contributions to your lab team during this unit.
    a. In your perspective, what are the most valuable contributions you have made to your team? Provide at least two specific examples.
    b. In your perspective, what is one action that you could take to improve your participation with your team?
    c. Set a long-term goal(s) for yourself that focuses on improving your collaboration while working in a team.
    d. In what ways can you work toward this goal during labs?
    e. How will you know if you're making progress toward your goal?
    f. What is a specific step that you can take in lab next week?

Group name: _____________ Group members: 1.____________2.____________

Unit 3: Model Building and Design

Learning goals:

By the end of this unit, you should be able to:

- Design high-precision experiments to build models, including identifying interesting variables to test, controlling variables, and reducing uncertainty and systematics [Goals: 1. a) i, ii, iii, 1.b) i, ii.].
- Manage time by conducting pilot experiments, plotting as you go, and reflecting on the measurements and data throughout [Goal: 2. f) i, ii].
- Motivate all research questions, conclusions, claims, and interpretations with supporting data [Goal: 3.a), 4.d)].
- Provide positive and constructive feedback when evaluating peers' work [Goal: 5. c)].

Activity I: Investigating Magnets and Voltage Changes

Science is often executed in small pieces until larger meaning can be obtained. In this unit, you will be investigating one piece of a larger puzzle in detail to build towards a collective model. Your instructor will show you a demonstration at the beginning of this lab.

A. Propose model variables

Your first task is to brainstorm with your group about all the possible variables that may affect what is happening in the demonstration, categorizing them based on whether they are testable with the available resources.

Testable	Possibly testable	Not testable

B. Isolate and test the effects of a single variable

Your instructor will assign your group a single variable to test. In your group, devise a plan to qualitatively and quantitatively test the effects of that variable. You may use any equipment or measuring devices that are available in the lab (that you know how to use) and any additional equipment that has been brought in for this lab.

Variable you are testing:

Predictions for the effect of that variable on aspects of the demonstration:

In your lab notes online, document your experimental plan, your predictions, and your observations and data. Use your investigations to build a model that is both *explains* the effect of the variable and makes new predictions.

Use your evidence to propose several possible models and compare your data to each model. Iteratively build a body of evidence that rules out possibilities and provides support for other possibilities.

At the end of the first session, your group will quickly report out to the class what you have found about the effects of the variable you're testing.

C. Present results to build a collective model

At the end of the second session, you will give a **2-3 minute** presentation (one minute per group member). In your presentation, you should provide:

(1) a short explanation of your variable,
(2) a very brief summary of the tests you conducted,
(3) **one or two** major results or observations, and
(4) at least one possible way to continue to test the variable or improve your measurements.

As an audience member, you should write down one question for each presentation that seeks to clarify, extend, or complement aspects of the project or presentation.

FAQ: How do I get a signal to appear on the oscilloscope?

1. *Have you discussed an appropriate time scale with your group?* Adjust the timescale manually to an order of magnitude that is appropriate for your test (e.g., how long does it take for the magnet to fall through the coil?).
2. *What is the trigger?* Triggering is the process of starting a "sweep" of the oscilloscope. The oscilloscope waits for the voltage difference to pass through a "triggering voltage" before beginning a new sweep. We want the triggering voltage to be high enough to avoid triggering on noise but low enough to detect the induced voltage difference from the test. The triggering voltage is adjusted via the knob labeled "Trigger". The oscilloscope allows you to set various properties associated with the trigger. Start with the trigger type set as "Edge" and the trigger mode set as "Normal".
3. *How do I get the signal to "freeze" on the screen?* The "Single" button on the upper right-hand corner of the oscilloscope should be green before you conduct a test. When the triggering voltage is reached, it will turn red and "freeze" the trial on the screen of the oscilloscope.
4. *How do I measure [insert measurement]?* The oscilloscope has many available tools to assist you in making different measurements. The Multipurpose knob and the "Math" button each include multiple capabilities that are available. Search online for the oscilloscope manual (include brand and model number) for additional information.

Unit 3 – Session 1 Post-lab

1. Reflect on your process and findings from last week.
   a. What variable did you investigate?
   b. What results did you obtain and what conclusions did you draw?
   c. Are there any other possible interpretations for your data?
   d. What new questions do you have about the model or methods?
2. Reflect on your experiences and opportunities to work toward your goal (previous prelab) during lab and outside of lab (perhaps even outside of an academic context!).
   a. In what ways could acting as a Principal Investigator help you work toward the goal in these situations? Reviewer #2? Science Communicator?
   b. How do you see working toward your goal helpful or useful to your future collaborations (academic and non-academic, within physics and outside physics)?
   c. What are some additional steps you plan to take during lab in the coming weeks to work toward your goal?

Unit 3 – Session 2 Post-lab

1. Often, we use measurements to calculate other values and need to *propagate the uncertainty* from the measured values to the calculated ones. For example, if you were to measure the length of a table with a 30 cm ruler (placing the ruler repeatedly along the length of the table and adding up the cumulative lengths) you would have about 0.5 mm uncertainty in each measurement from the ruler. The total uncertainty in the measured length would have to add up the uncertainties each time. The exact rules are slightly more complicated, however.
   a. Explain the idea of uncertainty propagation in your own words. Provide examples of when propagating uncertainty would have improved your analyses and/or conclusions in previous labs (in this or another course).
   b. Using the materials in the Statistics Summary on Page 31, propagate uncertainty through the following functions for the measurements $\boldsymbol{x \pm \delta x}$ and $\boldsymbol{y \pm \delta y}$.
      i. $\boldsymbol{f(x) = Ax^2}$
      ii. $\boldsymbol{f(x) = B\tan x}$
      iii. $\boldsymbol{f(x, y) = C\ln x + y}$
      iv. $\boldsymbol{f(x, y) = Fxy}$
      v. $\boldsymbol{f(x, y) = Gx\tan y}$

      Note: In each case, capital letters are constants with no uncertainty.
   c. How would the uncertainty in *f(x)* in each case in (b) simplify if $\boldsymbol{\delta y \approx 0}$**?**

Unit 4: What does this thing do?

Learning goals:

By the end of this unit, you should be able to apply all of the skills you've learned thus far in lab to explore a new research question inspired by observations.

Activity I: Testing and developing circuit models

In this lab, you will be experimentally testing models that explain how an LED works. Your instructor will show you several demonstrations that you should use to motivate your investigations. You may also build from your previous experiments and you may use any of the materials used so far in this course.

To ensure no circuit elements or measuring devices will be destroyed: *Make estimates and record your reasoning that demonstrates the circuit is safe and equipment should not break (especially resistors, DMM, and light bulbs).*

A. Plan your own experiment

Work with your group to brainstorm several models to explain how LEDs work, based on your demo. Models must be developed from evidence, which will require testing several relationships between variables. All variables or parameters included in the model must be measurable or calculable with the equipment available in the lab.

Plan and sketch an outline of a series of experiments to test your models. Include a decision tree for how you plan to carry out the experiments (a sketch of your plan with multiple pathways and/or loops based on each (un)expected result).

Carry out your experiment according to your decision tree and note when and why you deviate from the plan. You should confer with other groups.

B. Present your process

At the end of the second session, you will give a 3-5 minute presentation to the class including:

1) a short explanation of your model,
2) a very brief summary of the experiment(s) you conducted,
3) **one or two** interesting results or observations, and
4) at least one possible way to continue to test or improve the model.

Prepare your presentation on your group whiteboard. You will have to leave out a lot of details (but all the gory details should be in your lab notes)! Submit a photo of your whiteboard along with your lab notes.

Unit 4 – Session 1 Post-lab

1. Summarize your investigation from Session 1 and how you will proceed in the next lab.
    a. What variable, system, and/or question are you testing?
    b. Why is this variable, system, or question interesting?
    c. What aspects of the measurement methods introduced the most variability (either statistical or systematic) and how might you improve on those methods?
    d. What do you think your group should do in the final lab session?

Unit 4 – Session 2 Post-lab

1. Please make sure your group has submitted a photo of your lab presentation online.

Grading Criteria: Lab notes

Your lab notes will be graded according to the course goal:

Goal	Category	Expert	Proficient	Developing
Collect data and revise an experimental procedure iteratively and reflectively,	*Experiment Design*	*Researchers appropriately answer the research question:*	*Answers research question, but with some limitations:*	*Has very limited ability to answer the research question:*
	• **Consideration, control, & testing of variables**	Done carefully for several primary & secondary variables.	Done for a primary variable.	Not done or inadequate.
	• **Pilot tests**	Always done.	Limited use.	Missing.
	• **Improvement/refinement of experiment design**	Done iteratively based on data, pilot trials, and/or discussions with other groups.	Done iteratively, but some evident modifications not made.	Designs haphazard or not developed iteratively. Evident modifications not made.
	• **Methods to reduce uncertainty**	Identified & incorporated as much as possible and practical.	Identified & incorporated.	Limited, missing, or impractical.
	• **Seeking solutions to technical problems**	Practical & creative, based on physics.	Practical, based on physics.	Limited, impractical, inappropriate, or missing.
	• **Excellence**	Go above & beyond necessity, incorporating innovative/unique ideas into experiment design.		

Goal	Category	Expert	Proficient	Developing
Evaluate the process and outcomes of an experiment quantitatively and qualitatively.	***Use of methods to analyze data***	*Appropriate methods are used:*	*Appropriate methods are used:*	*Methods to analyze data are absent or limited:*
	• **Major sources of uncertainty**	Identified, quantified, & prioritized	Identified & quantified.	Not identified or are inappropriately quantified.
	• **Graphs of data**	Clearly portray results & trends.	Reasonably portray results.	Missing or inadequate.
	• **Statistical tools to represent & analyze data**	Used in various different appropriate ways.	Used appropriately.	Used inappropriately or not used.
	• **Claims & interpretation about results & findings**	Supported by appropriately evaluating methods, data, analysis, and other evidence.	Supported by appropriately evaluating methods, data, analysis, and other evidence.	Not adequately supported by data, observations, or other evidence. Weak use of physics.
	• **Soundness of approach & analysis, possibly affecting interpretation**	No errors made that might affect interpretation of experiment.	Only minor errors made, not significantly affecting experiment interpretation.	Significant errors made, affecting experiment interpretation.
Extend the scope of an investigation whether or not results come out as expected.	***Interest and ambition of independent experiments, as opportunities arise and permit***	*Researchers' independent experiments are ambitious, yet feasible & justifiable:*	*Researchers' independent experiments are feasible & justifiable:*	*Researchers' independent experiments are limited:*
	• **Explicit and interesting research questions**	Interesting/creative questions are explicit with answers not already known.	Questions are explicit with answers not already known.	Questions are vague, missing, or answers already reasonably known.
	• **Justification based on data or physics**	Questions motivated & justified by prior data or physics.	Questions motivated & justified by prior data or physics.	Questions not clearly justified or motivated by prior data or physics.
	• **Ambition & challenge with allotted time & materials**	Ambitious research questions that can be reasonably and feasibly explored.	Research questions can be reasonably and feasibly explored.	Research questions unfeasible with allotted time & materials.

Goal	Category	Expert	Proficient	Developing
Communicate the process and outcomes of an experiment.	***Communicate research processes & thinking***	*Researchers use lab notes and presentations clearly:*	*Researchers use lab notes and presentations adequately:*	*Lab notes & presentations are limited:*
	• **What are you doing? (Description of process)**	Process described clearly so a reader can easily understand all of what was done.	Process described clearly so a reader can understand most of what was done.	Important descriptions missing, or a reader can't understand what was done.
	• **Why are you doing it? (Justification of process)**	All decisions justified so a reader can easily understand why actions were done.	Most decisions justified so that a reader can understand why actions were done.	Decisions unjustified, or a reader can't easily understand why actions were done.
	• **Presentation of data, key calculations, and diagrams**	Presented clearly so a reader can easily interpret results.	Presented clearly so a reader can interpret results.	Missing or are presented such that a reader can't interpret results.
	• **Lab notes are a clear stream of consciousness.**	Yes, not a formal lab report.	Reasonably clear and mostly as stream of consciousness.	Unclear or written as a formal lab report.
	• **Lab notes demonstrate reasonable effort.**	Researchers put in reasonable effort but didn't devote excessive lab time to lab notes, compared to actual lab work.	Reasonable effort shown, but excessive lab time may have been devoted to lab notes.	Little effort shown, or lab notes consumed excessive lab time.
Conduct an experiment collaboratively and **ethically**.	***Addressing ethical concerns or biases***	*Plan & experiments attend to ethical concerns or biases:*	*Plan & experiments attend to ethical concerns or biases:*	*Plan & experiments rarely or inadequately attend to these:*
	• **Strategies to manage biases & expectations**	Various practical and creative strategies actively employed in investigations.	Practical strategies actively employed in investigations.	Superficial, impractical, or missing strategies, or suggested strategies are not actively employed.
	• **Consider how expectations may affect decisions**	Researchers explicitly consider possible consequences.	Researchers reflect on this.	Researchers rarely reflect on this.
	• **Consider alternative models or explanations**	Various creative and plausible explanations or models are considered and evaluated.	Alternative explanations or models are considered.	Alternative explanations or models are never, rarely, or only superficially considered.
	• **Seeking disproof**	Disconfirming evidence sought regularly and actively as part of the investigation.	Disconfirming evidence sought.	Disconfirming evidence rarely or never sought. Exclusive focus is on confirming a model or expectation.

Grading Criteria: Participation

Your participation in lab each week will be graded according to the course goal:

Goal	Category	Expert	Satisfactory	Developing
Conduct an experiment **collaboratively** and ethically.	***Effectiveness and productivity of group***	*Researchers work effectively & productively as a group:*	*Researchers work effectively as a group:*	*Group work is not always effective or productive:*
	• **Brainstorming and discussion of ideas**	Done together, with all group members contributing to decisions.	Done together, with most group members contributing to decisions.	Some members don't contribute, individual ideas ignored/excluded, or one member dominates.
	• **Equity of contributions to investigation**	All group members contribute equally. Any distinct roles rotate within or between lab sessions.	All group members contribute. Any distinct roles rotate within or between lab sessions.	Group members don't contribute equally. Distinct roles not rotated or shared. One member dominates.
	• **Constructive questions that support discussion and offer insight**	Group members ask constructive questions and encourage & actively solicit ideas/opinions, especially from those who tend to hold back.	Group members ask constructive questions.	Questions are absent or not constructive.

Statistics Summary

I. Measurement and Uncertainty

The process of doing an experiment in physics involves collecting and understanding data. Data are obtained through measurements with various instruments. With every measurement comes some uncertainty.

There are two general categories of uncertainty: systematic and statistical. ***Systematic uncertainties*** cause measurements to be consistently too high or too low. These can result from various measurement and physical influences such as instrument calibration or variables inappropriately assumed to be negligible. If all systematic uncertainties are identified and accounted for, we could eliminate systematic uncertainty. However, this is usually impractical and, possibly, impossible. ***Statistical uncertainties*** are random variations in measurements that occur with any measurement. These uncertainties may arise from limitations in measuring devices or fluctuations in the physical system and typically occur in both the high and low directions. We can reduce, but never eliminate, statistical uncertainties from our experiments. All measurements have uncertainty, and they may have both statistical and systematic uncertainties from a variety of sources.

Measurements are often also described as being either ***precise*** or ***accurate***. Precision and accuracy are independent of one another. If you're throwing a ball at a target, you would be very accurate if the ball hit around the target each time. If you hit the target each time, then you would be precise and accurate. However, if you were aiming for the target and hit a nearby tree at almost exactly the same spot each time, you would be precise but not accurate. Measurements that are very ***precise*** have small uncertainty**.** Measurements that are close to a predicted or standard value are referred to as ***accurate***. It is necessary to understand how precise (or uncertain) our measurements are before making any claims about our accuracy. It's not helpful to average around the target if our throws are all over the place, such as hitting every tree on all sides of the target, but not hitting the target itself!

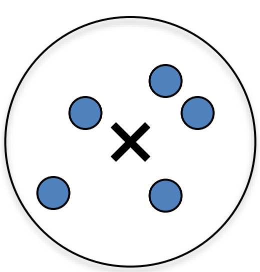


Fig. 1 Accurate

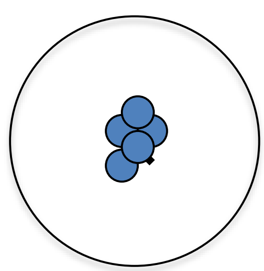


Fig. 2 Accurate & Precise

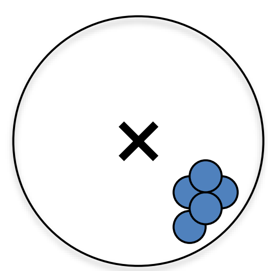
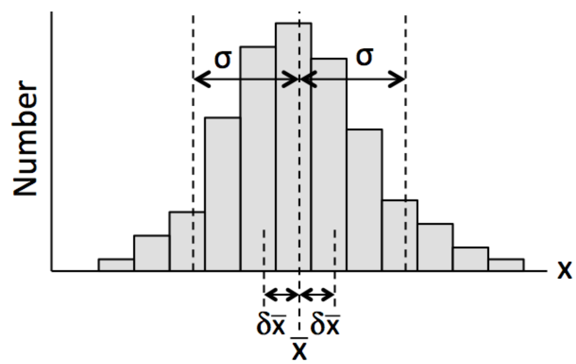


Fig. 3 Precise

In previous science classes you may have encountered ***significant figures*** (often called "sig figs"). For each measurement, the final (rightmost) digit communicates to a reader something about the precision of the measurement. Instrumental precision and significant figures are related because the final significant figure is an estimate based on the instrument's precision. Often other statistical uncertainties are much greater than the instrumental precision, so it is important to consider the greatest contributing factor to each measurement's uncertainty.

II. Statistics for Repeated Measurements with Statistical Variation

In some situations, you will be able to repeat a measurement many times in order to assess the uncertainty caused by statistical sources of variation. If you take enough measurements, you can draw a histogram that displays how frequently the measurement lands in different ranges of values.



Several things can be seen in such a histogram (see below). First, the data is often clustered in some way and mathematically we estimate the value they are clustered around by calculating the ***mean***. If x_i are the measured values and if you took N different measurements ($i = 1, \dots N$), the mean is calculated using:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

Note that the mean $\bar{x}$ is still an estimate based on a finite number of measurements, and if you kept taking more measurements the mean would change somewhat.

The second thing to notice in the histogram is that the values are distributed on either side of the mean value, with some characteristic width. The width is usually expressed in terms of the ***standard deviation*** σ:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

About 68% of the measurements will lie within the range from $\bar{x} - \sigma$ to $\bar{x} + \sigma$. However, if you have gone through the trouble of taking N different measurements, the uncertainty in the mean value $\bar{x}$ is smaller than the standard deviation. The ***uncertainty in the mean*** of all your measurements is called the ***standard uncertainty*** $\delta\bar{x}$ given by:

$$\delta\bar{x} = \frac{\sigma}{\sqrt{N}}$$

This serves to reward you for taking more data, so that the uncertainty in the mean of a collection of many measurements is smaller than the uncertainty in any single measurement. If you do one hundred times as many measurements, the uncertainty only decreases by a factor of ten – hard work!

III. Uncertainty due to instrumental precision

Not all uncertainty, however, comes from repeated measurements. If you use a ruler to measure the length of the table, repeating the measurement is not going to give you a different number. Sometimes, the only thing limiting the reliability of your measurement is the finite scale of the measuring device.

Analog instruments (e.g., a ruler) can often be read to about a half or a quarter of the smallest increment. For example, if a ruler measures to the nearest millimeter, we can typically distinguish whether a measurement falls between the two increments and whether it's closer to one line or another. The uncertainty, therefore, is *at most* half the smallest increment of the scale; 0.5 mm in this example, though most rulers can be read to 0.25 mm.

Digital instruments have uncertainty due to the rounding of the number. For instance, a digital reading on a scale might display 24.5 kg, which means that the mass could be anywhere between 24.45 and 24.55 kg. The uncertainty, therefore, is half the smallest increment of the scale (0.05 kg in this example).

IV. Making Comparisons

The quantity that we use to make comparisons between numbers is known as $\boldsymbol{t'}$ ("t-prime"). If we have two numbers with uncertainties, $A \pm \delta A$ and $B \pm \delta B$. Then their $\boldsymbol{t'}$ value is:

$$t' = \frac{A - B}{\sqrt{(\delta A)^2 + (\delta B)^2}}$$

After calculating t' for two measurements, you can evaluate their similarity (or distinguishability) through the following interpretation:

- $|t'| \leq 1$: A and B are indistinguishable compared to the uncertainty (very likely the same). Remember though, if you do a better measurement to decrease the uncertainties, you might later uncover a difference between A and B. That is, poor precision may be hiding a subtle difference!
- $1 < |t'| \leq 3$: It is possible that A and B are the same, but they are not clearly indistinguishable.
- $|t'| > 3$: It is very unlikely that A and B are the same.

For $|t'| \leq 1$, you may need to consider:

- Improving your measurements,
- Decreasing uncertainties, or
- Checking that you've appropriately accounted for uncertainty.

For $|t'| > 3$, you may need to consider:

- Retaking or improving your measurements, or
- Evaluating your model and possibly revising it.

Mini-lecture: youtu.be/J8E9jgsB8Zs

V. Fitting by the Method of Weighted Least-Squares

When fitting any function to a set of data, one tries to find a model with parameters that can minimize the 'distance' between the data points and the function.

Consider a function $f(x)$ and a set of measurements consisting of x_i and y_i values and an uncertainty δy_i in each measured y_i . The 'distance' between a data point and the function is given by the residual $y_i - f(x_i)$.

A measure of how close the function is to the data overall is given by the weighted χ^2:

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(y_i - f(x_i)\right)^2}{(\delta y_i)^2}$$

The ***method of least squares*** means finding a function with parameters that minimize χ^2 ("chi-squared", pronounced 'kye-squared'). For instance, if you are fitting a straight line with the form $f(x) = mx + b$, you would vary the parameters m and b until you find the minimum χ^2 . The fit can be done iteratively by trial and error or, for one or two parameter models, analytically minimized using calculus principles.

A benchmark for a good fit would be a χ^2 value close to 1. In that case, the scatter in the data, on average, would be comparable to the estimated uncertainties. A χ^2 value much greater than one suggests either a bad fit or underestimated uncertainties. A χ^2 value much less than one probably means that you have over-estimated your uncertainties.

For a large χ^2 value, you may need to consider:

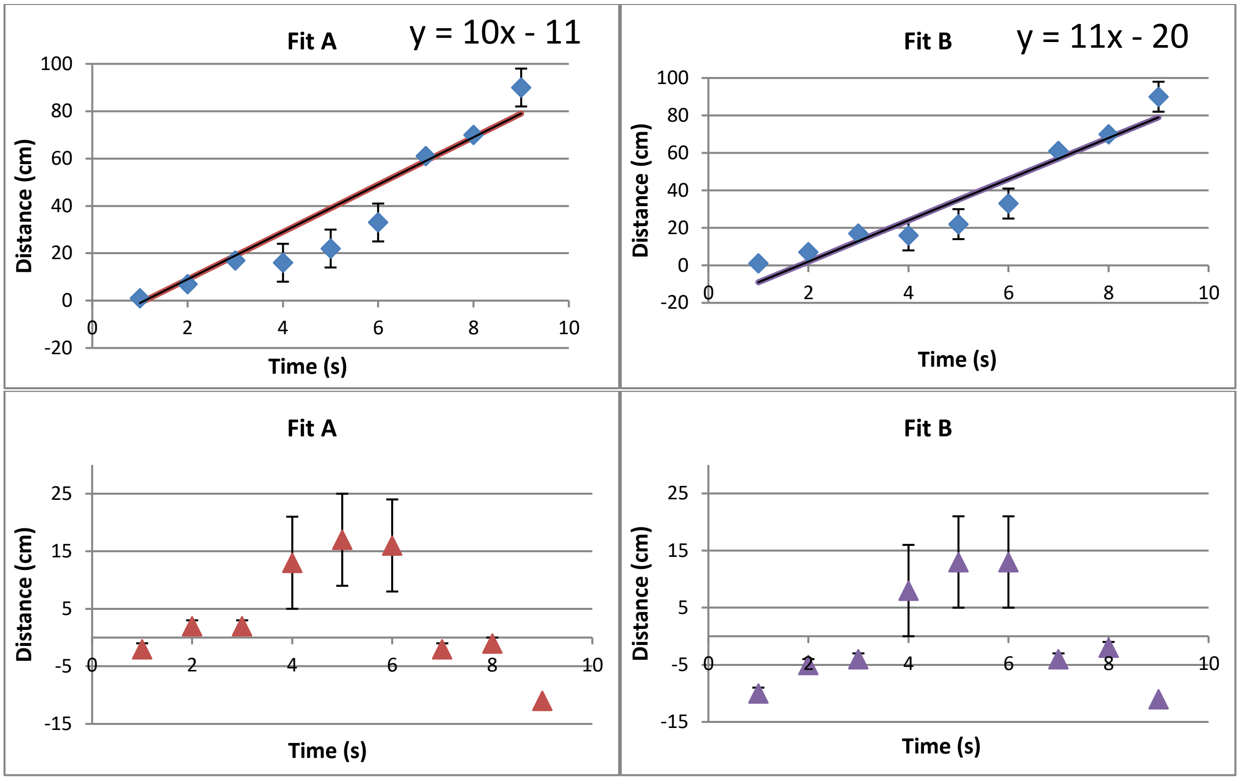
- Retaking or improving your measurements,
- Checking that your uncertainty makes sense, or
- Evaluating your model and possibly revising it.

For a small χ^2 value, you may need to consider:

- Checking that you've appropriately accounted for uncertainty, or
- Decreasing uncertainties or improving your measurements.

Note that χ^2 uses the uncertainty in each measured value. If you search online, you may notice that many different definitions of χ^2 exist, including those that don't take uncertainties into account. Consider the two graphs below, which have different fit lines to the same data.

Mini-lecture: youtu.be/UX4Jm33TM3E



In Fit A, the line is closer to the more precise measurements (the ones with smaller uncertainty). This is a *weighted* fit using the method of *weighted least squares linear regression* to calculate χ^2. Because you are making measurements and finding evidence for which model appropriately describes your data, the better (more precise) measurements should "count" more when fitting your data.

In Fit B, the line does not give preference to the precision of the measurements, giving an *unweighted* fit using the method of *unweighted least squares regression*. While this may look visually appealing, this fit does not consider that several measurements have much better precision than others. Obtaining more precise measurements can allow you to uncover small effects, so the precision of measurements should matter when determining which model best describes your data.

As expected, weighted and unweighted least squares regression analyses will give you different outcomes for the fitting parameters and the quality of the fits. In this class, we will always use weighted fits. If uncertainties are the same across all measurements, the two methods should give the same outcomes for the fitting parameters such as m and b (although the χ^2 values will differ between the two methods).

	Weighted χ^2	Unweighted χ^2
Fit A	**3.3**	94.7
Fit B	**18.8**	76

If a quantity that you're calculating has more than one source of uncertainty (i.e., you're multiplying two measurements together), then there is uncertainty in the final quantity.

- If you have recorded two measurements, $A \pm \delta A$ and $B \pm \delta B$, and are determining the ***sum*** or ***difference*** $R = A \pm B$, the uncertainty in R is best estimated as:

  $$\delta R = \sqrt{\delta A^2 + \delta B^2}$$

  This applies whether adding or subtracting A and B—their uncertainties are always *added* quadratically. This idea is used in our definition of t'.

  You might expect the uncertainties δA and δB simply to add, but this would overestimate the uncertainty δR because random fluctuations in A and B aren't correlated, i.e., they don't always occur in the same directions.

- If you have recorded two measurements, $A \pm \delta A$ and $B \pm \delta B$, and are determining the ***product*** $R = AB$ or ***quotient*** $R = A/B$ with uncertainty δR:

  $$\delta R = |R|\sqrt{\left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta B}{B}\right)^2} = |AB|\sqrt{\left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta B}{B}\right)^2}$$

  Note that this time we add the *relative* (or *fractional*) uncertainties quadratically. This works for multiplication and division of any number of quantities that have uncertainty. For example, if $R = \frac{AB}{C}$ then:

  $$\delta R = \left|\frac{AB}{C}\right|\sqrt{\left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta B}{B}\right)^2 + \left(\frac{\delta C}{C}\right)^2}\ .$$

- If you're raising a quantity with uncertainty, $X \pm \delta X$, to a ***power***, $R = X^n$, then the uncertainty is $\delta R = |n|\frac{\delta X}{|X|}|R|$. Calculation of uncertainty through powers should be completed before uncertainty is calculated for multiplications, additions, etc.

<u>Example</u>. In calculating a value for kinetic energy $K = \frac{1}{2}mv^2$, the uncertainty in v^2 should be calculated first: $\delta(v^2) = 2\frac{\delta v}{|v|}v^2$. Then the uncertainty in K would be calculated:

$$\delta K = K\sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta(v^2)}{v^2}\right)^2} = K\sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{2\delta v}{v}\right)^2}.$$

No uncertainty term is included for the factor of 1/2 since it is considered to be exact (uncertainty = 0). If the mass m happened to be the difference of two measured masses, $m = m_1 - m_2$, then $\delta m = \sqrt{\delta m_1^2 + \delta m_2^2}$.

- In general, if you are computing any function, $R = f(X_1, X_2, \ldots X_n)$, where each X_i has associated uncertainty δX_i, then:

$$\delta R = \sqrt{\left(\frac{\partial f}{\partial X_1} \cdot \delta X_1\right)^2 + \left(\frac{\partial f}{\partial X_2} \cdot \delta X_2\right)^2 + \cdots \left(\frac{\partial f}{\partial X_n} \cdot \delta X_n\right)^2} \, .$$

This relationship generates the three "rules" above. For example, for $R = A + B$:

$$\delta R = \sqrt{\left(\frac{\partial R}{\partial A} \cdot \delta A\right)^2 + \left(\frac{\partial R}{\partial B} \cdot \delta B\right)^2} = \sqrt{\delta A^2 + \delta B^2}$$

because each derivative is equal to 1. We leave it as an exercise to demonstrate that this relationship reproduces the other "rules" above.

Excel Tutorials

I. Making a Plot

1. Begin by selecting the data to be graphed. Click on the "Insert" tab and find the appropriate chart for the data you are graphing (in this case, a scatter plot, Figure 1).

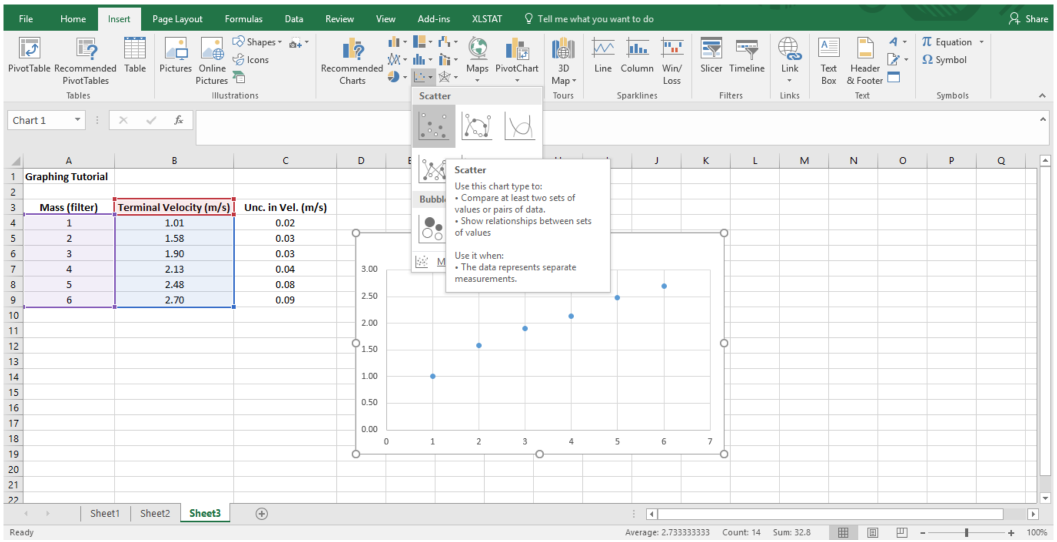


Figure 1: Selecting data to make a scatter plot.

2. Label your axes as in Figure 2. You are able to add a variety of features and change the layout to your liking.

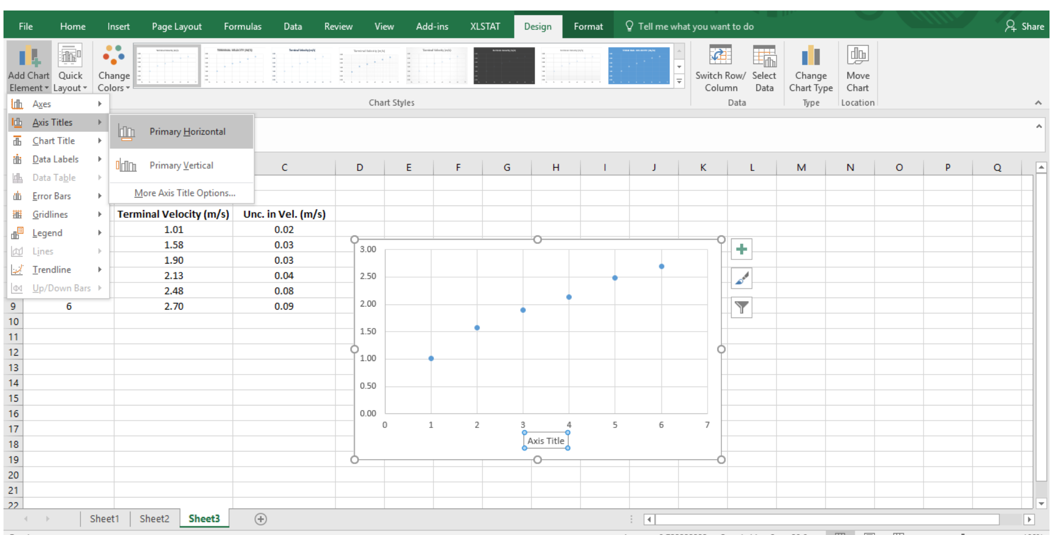


Figure 2: Inserting labels on the axes.

3. Figure 3 shows how to adjust the axes scales and limits.

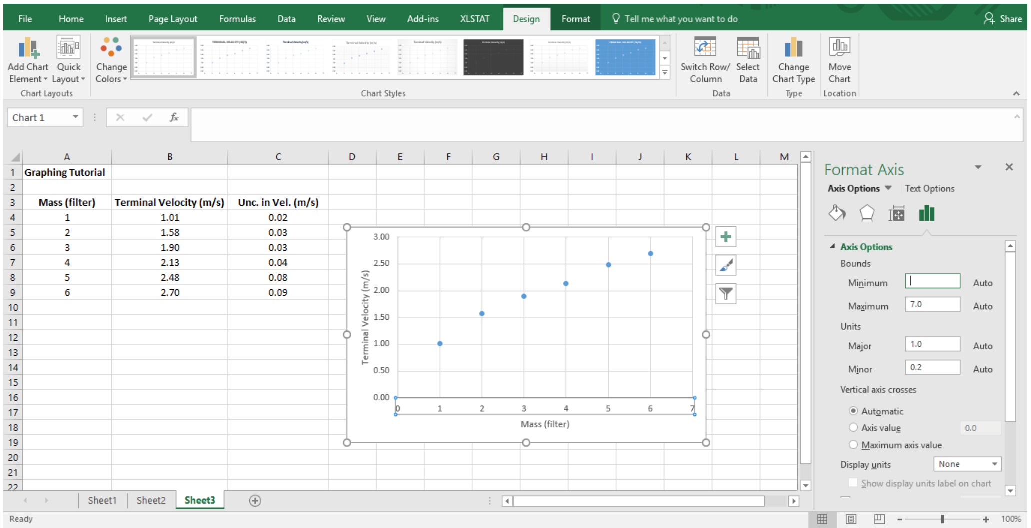


Figure 3: Adjusting axis bounds.

II. Adding uncertainties to the plot

1. Create a column with the uncertainty in each of your data points. Uncertainty is represented in Excel through "error bars". Next go to "Add Chart Element" -> "Error Bars" -> "More Error Bars Options…", as shown in Figure 4.

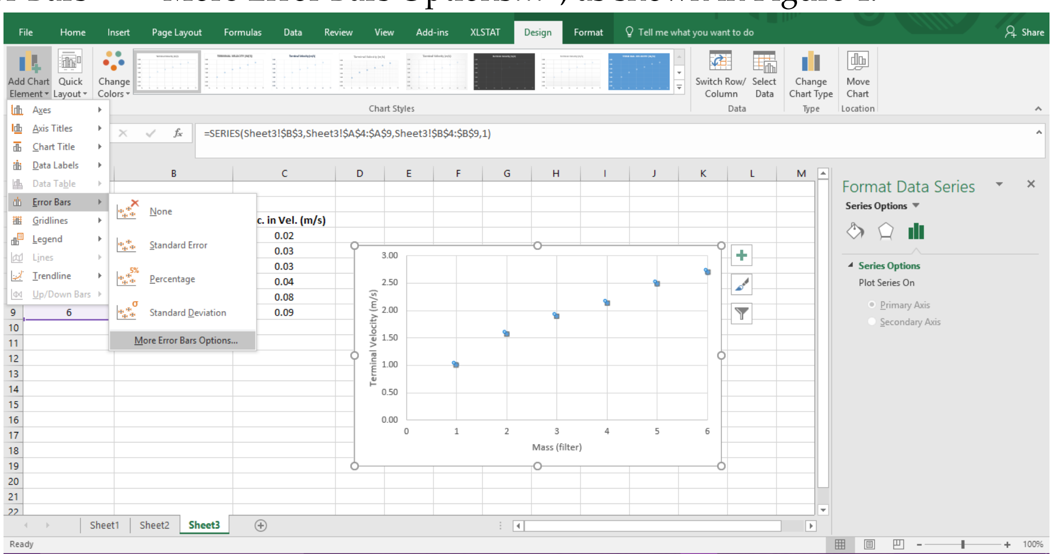


Figure 4: Adding in representations of uncertainty in Excel.

2. Uncertainties appear that do not represent the uncertainty in your data. Select the error bars in the "y-direction". On the righthand side, scroll down to the bottom option and select "Custom" by clicking on the "Specify Value" button (Figure 5).

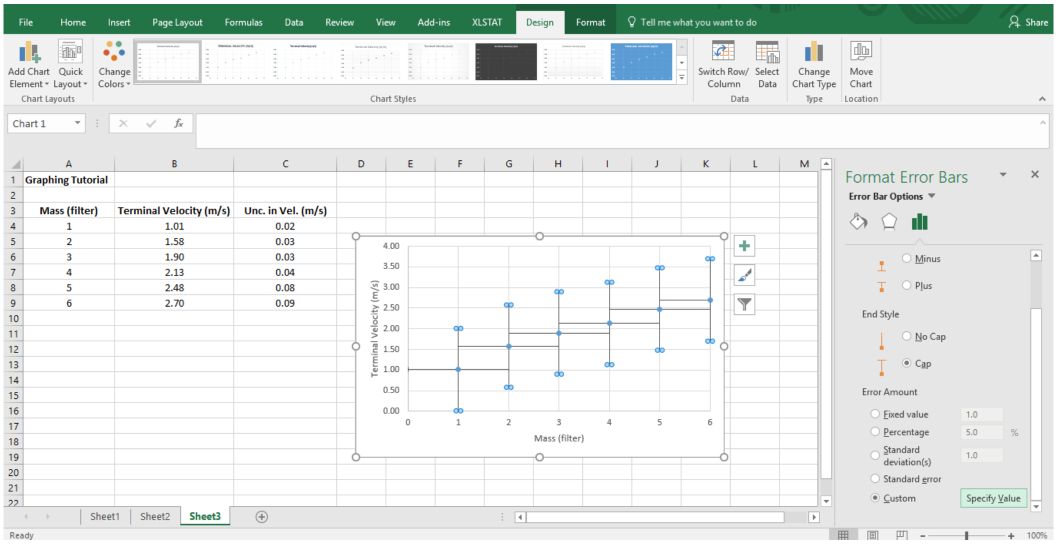


Figure 5: Specify uncertainty using custom values.

3. In the pop-up (Figure 6), specify the cell range where you have recorded the uncertainty; in this case the "y-direction" represents the terminal velocity so the cell range is selected that lists the uncertainty of each terminal velocity measurement.

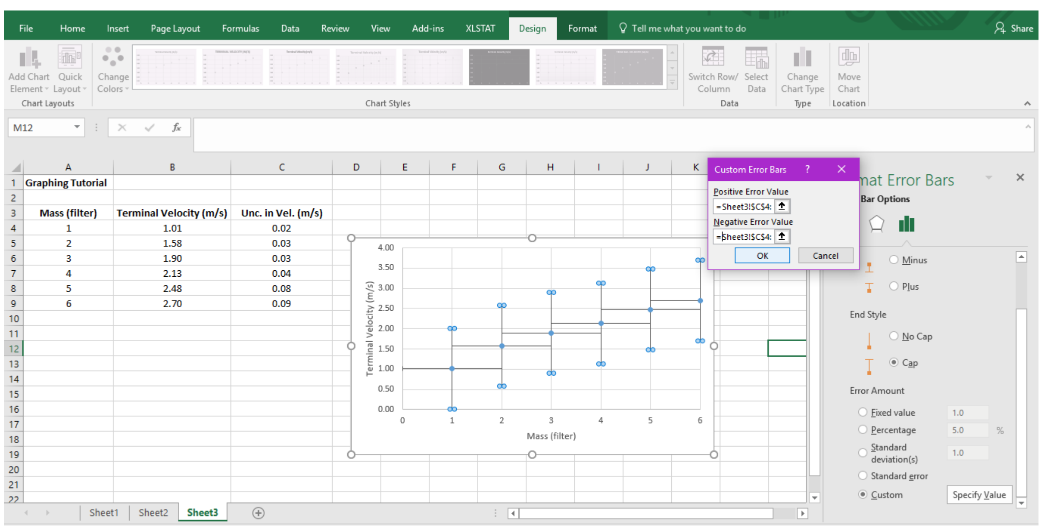


Figure 6: Selecting uncertainty to represent with error bars.

The uncertainty bars representing the uncertainty in the "x-direction" can be adjusted in a similar way.

III. Performing a weighted least-squares regression

The weighted least squares regression minimizes χ^2 which is expressed as:

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(y_i - f(x_i)\right)^2}{(\delta y_i)^2}$$

In this case, y_i refers to the measured terminal velocity, $f(x_i)$ is the modeled terminal velocity, and δy_i is the uncertainty in the measured terminal velocity.

1. Set up your spreadsheet with your x, y and δy values. Figure 7 shows the mass (x), the measured terminal velocity (y), and the uncertainty in the terminal velocity (δy).

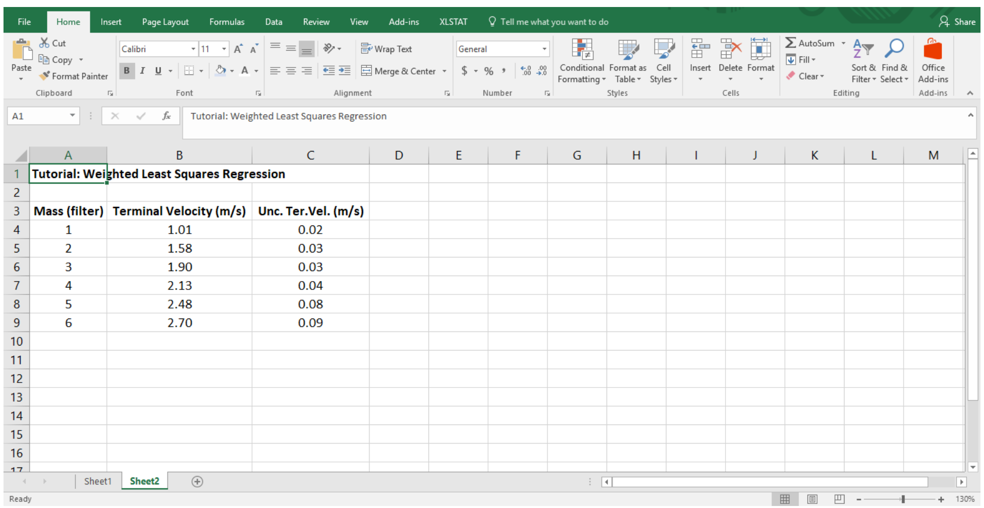


Figure 7: Data of mass and terminal velocity for coffee filters.

2. Calculate the modeled terminal velocity for each value of x: mx+b (Figure 8). Set up reference cells where you can change the values of "m" (E1) and "b" (E2).

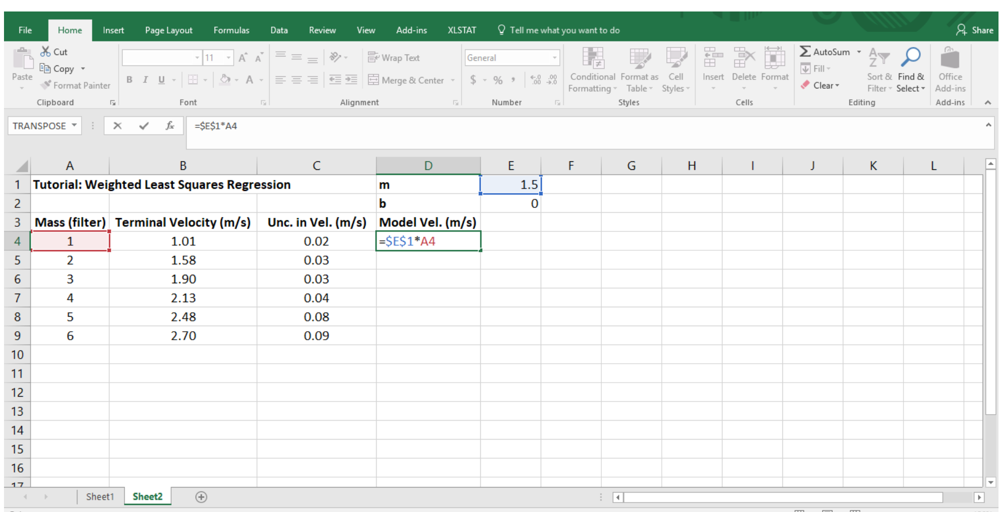


Figure 8: Calculating the model terminal velocity.

Permanent references to a single cell are written using "$", so E1 will always refer to cell E1. References that adjust based on location are written without $. Excel uses the following: Multiplication "*"; Division "/", addition "+", and subtraction "-".

3. Dragging the corner of a cell to other cells will produce the same formula or expression in the other cells (Figure 9). The reference cells that you did not set to be permanent will adjust according to their location.

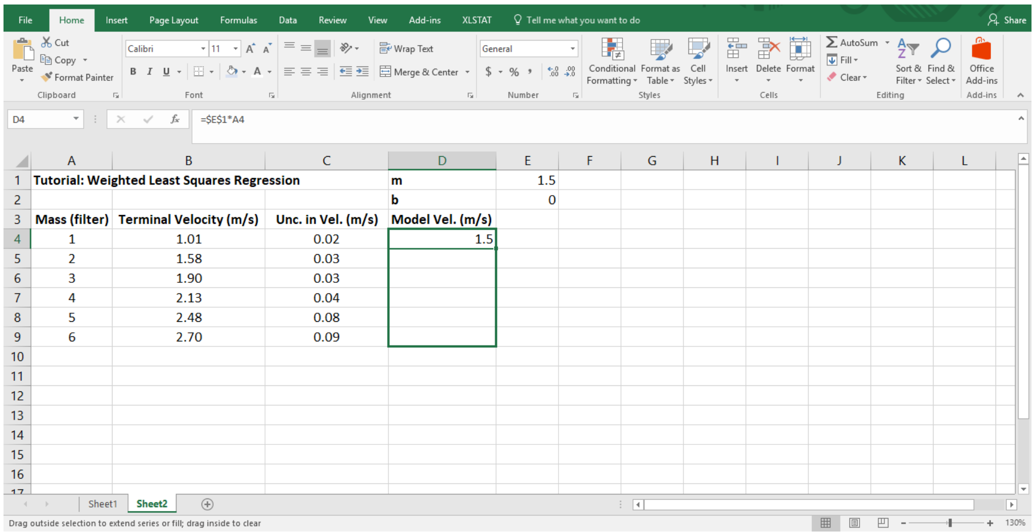


Figure 9: Dragging cells to distribute formulas.

4. The difference between the measured and modeled terminal velocities can be calculated by taking a difference. As show in Figure 10, the cell references should be adjusted based on location, so no "$" are used.

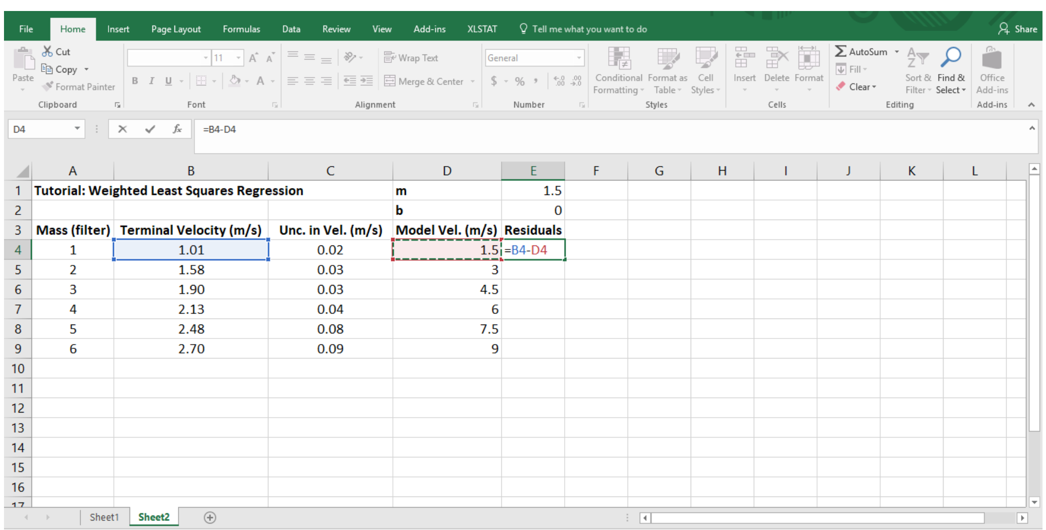
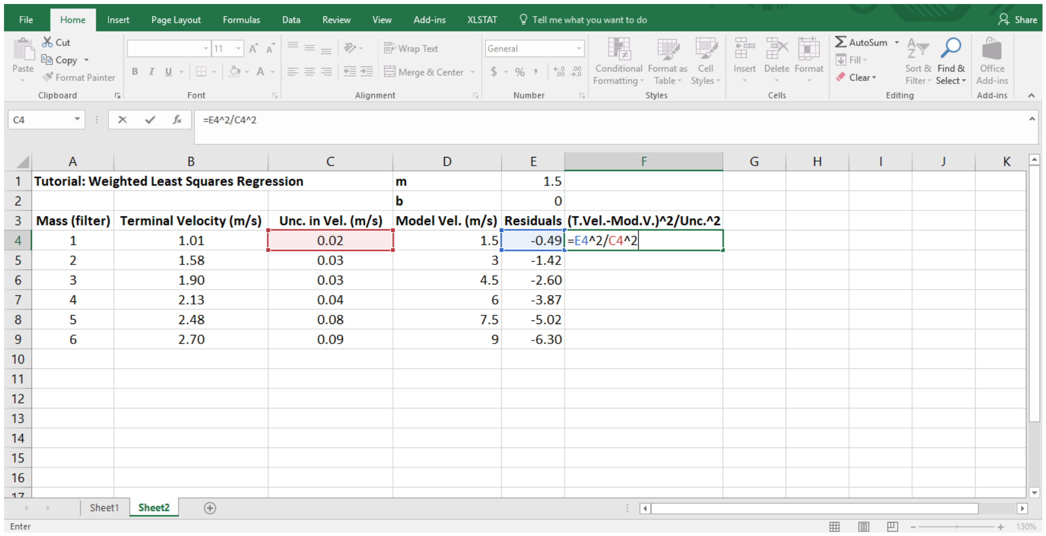


Figure 10: Calculating difference between measurement and model.

5. In a new column, square each residual and divide by the square of the uncertainty in the terminal velocity measurement. Exponents are expressed using a "^" symbol and division using a "/" symbol, as shown in Figure 11.

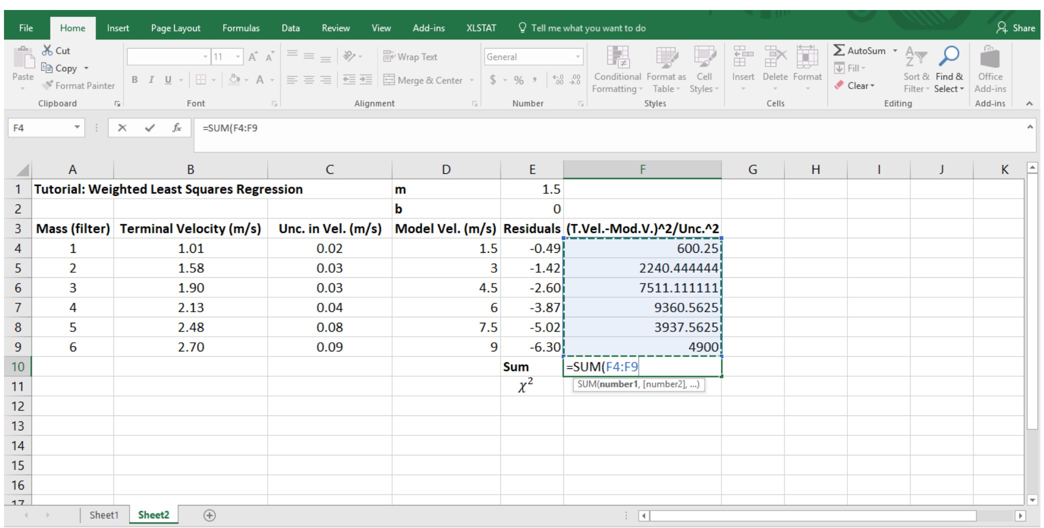


C4 =E4^2/C4^2

	A	B	C	D	E	F
1	Tutorial: Weighted Least Squares Regression			m	1.5	
2				b	0	
3	Mass (filter)	Terminal Velocity (m/s)	Unc. in Vel. (m/s)	Model Vel. (m/s)	Residuals	(T.Vel.-Mod.V.)^2/Unc.^2
4	1	1.01	0.02	1.5	-0.49	=E4^2/C4^2
5	2	1.58	0.03	3	-1.42	
6	3	1.90	0.03	4.5	-2.60	
7	4	2.13	0.04	6	-3.87	
8	5	2.48	0.08	7.5	-5.02	
9	6	2.70	0.09	9	-6.30	

Figure 11: Calculating the terms for χ^2.

6. Add the terms together using the SUM function: "=SUM(F4:F9)" where F4:F9 means all of the cells from F4 to F9 (Figure 12); equivalent to "=SUM(F4,F5,F6,F7,F8,F9)".



F4 =SUM(F4:F9

	A	B	C	D	E	F
1	Tutorial: Weighted Least Squares Regression			m	1.5	
2				b	0	
3	Mass (filter)	Terminal Velocity (m/s)	Unc. in Vel. (m/s)	Model Vel. (m/s)	Residuals	(T.Vel.-Mod.V.)^2/Unc.^2
4	1	1.01	0.02	1.5	-0.49	600.25
5	2	1.58	0.03	3	-1.42	2240.444444
6	3	1.90	0.03	4.5	-2.60	7511.111111
7	4	2.13	0.04	6	-3.87	9360.5625
8	5	2.48	0.08	7.5	-5.02	3937.5625
9	6	2.70	0.09	9	-6.30	4900
10					Sum	=SUM(F4:F9
11					χ^2	SUM(number1, [number2], ...)

Figure 12: Adding together values in multiple cells uses the SUM function.

7. Calculate χ^2 by dividing the sum by the number of data points (Figure 13). If you are using a large dataset, the number of data points can be calculated by using the COUNT function. In this case, "=COUNT(F4:F9)" outputs the number "6".

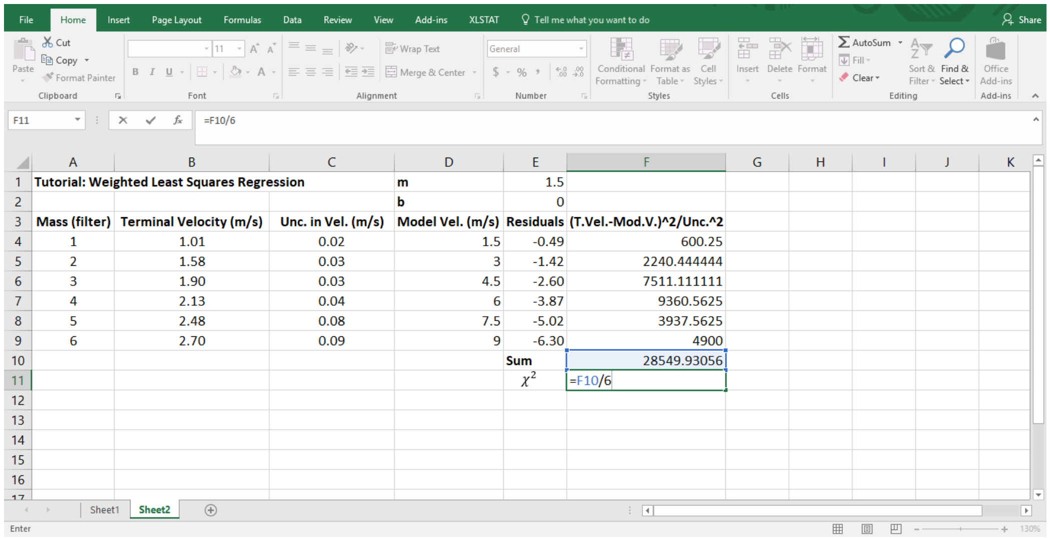


Figure 13: Calculating χ^2.

Adjust "m" and "b" to change the modeled terminal velocity values and minimize the χ^2. The spreadsheet should update all cells automatically as you change "m" and "b".

IV. Creating residual plots

1. Use methods from I to plot the residuals (difference between the measured terminal velocity and modeled terminal velocity) versus the mass (Figure 14)

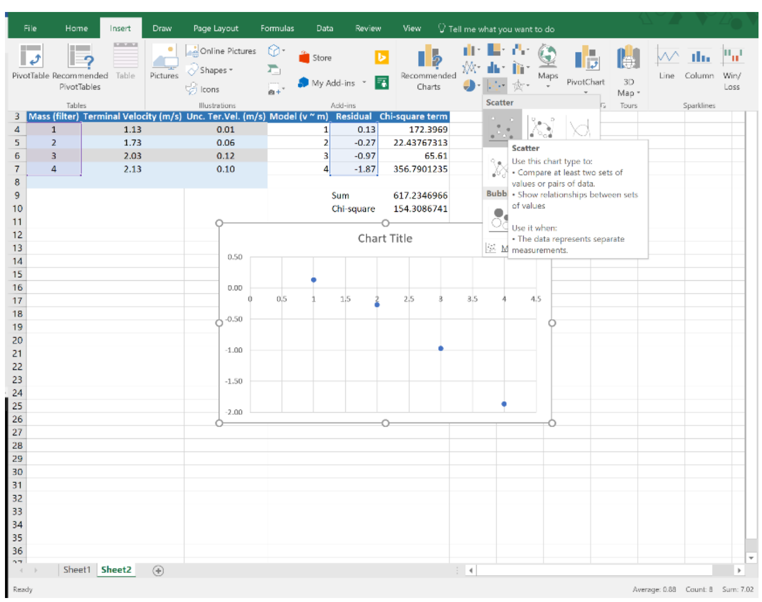


Figure 14: Select data for a scatter plot.

2. Add the uncertainties in the residuals (equal to the uncertainty in the y-values) and adjust axes labels and formatting to clearly communicate your plot (Figure 15)

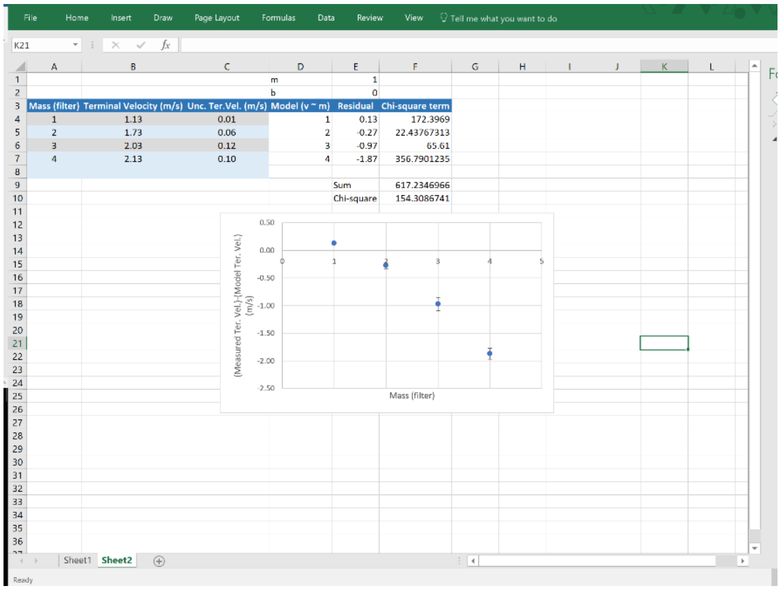


Figure 15: Adjust plot until it is easy to visually understand.

3. Adjust parameters until you minimize χ^2 and the residuals are randomly distributed around zero (Figure 16 does not quite have them minimized).

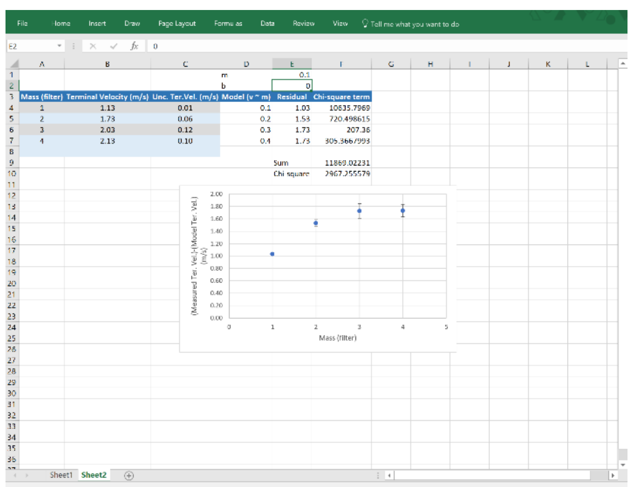


Figure 16: Adjust the parameters "m" and "b" to find a better fit. The fit is worse in this case.

V. Plotting the model and your data

1. Start with your measured and modeled terminal velocities are on a single spreadsheet and the scatter plot of your measured data (Figure 17).

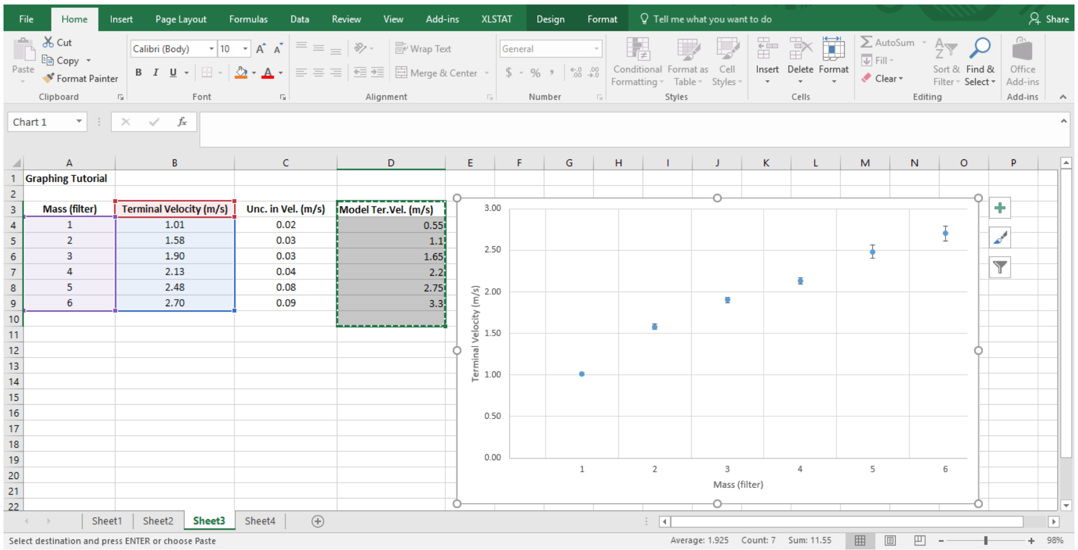


Figure 17: Copying model over to spreadsheet with measurements.

2. To add the model to the scatter plot, select the "Design" tab under "Chart Tools" and then click "Select Data" on the toolbar. Under *Legend Entries (Series)* in the pop-up (Figure 18), click the "Add" button to add the model series to the chart.

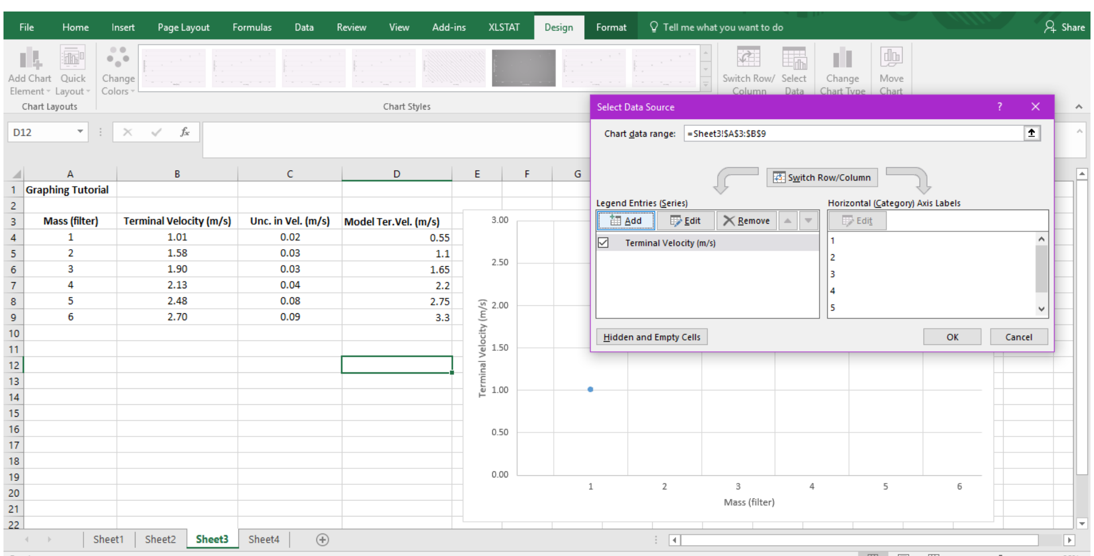


Figure 18: Selecting model series to include on chart

3. Type in a *Series name*, select the x-values to be the data set along the x-axis (filter mass in this case), and select the y-values to be the modeled terminal velocity (Figure 19).

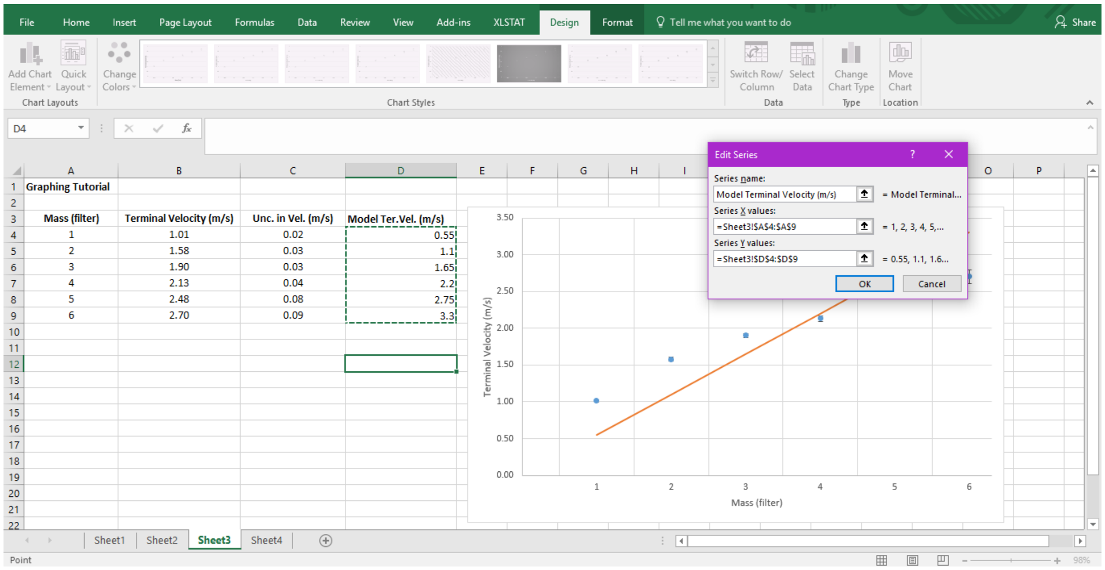


Figure 19: Selecting the model data for a new plot series.

4. If the chart does not show the data and model in a logical fashion, then select "Change Chart Type" on the tool bar and adjust the "Combo" type of chart until you are representing your data and model appropriately (Figure 20).

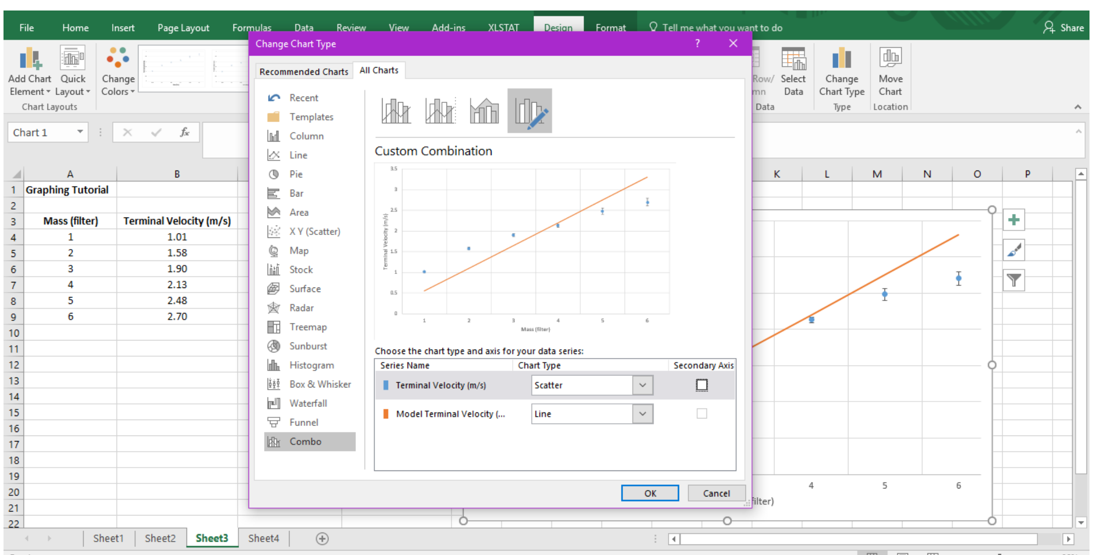


Figure 20: Selecting representations for measured and modeled terminal velocities.

Learning objectives and goals

By the end of the intro lab sequence, students should be able to:
1) Collect data and revise an experimental procedure iteratively and reflectively,
2) Evaluate the process and outcomes of an experiment quantitatively and qualitatively,
3) Extend the scope of an investigation whether or not results come out as expected,
4) Communicate the process and outcomes of an experiment, and
5) Conduct an experiment collaboratively and ethically.

Each objective has several more specific learning goals:

Objective 1: Collect data & revise the experimental procedure

a) Decide which data to collect, including:
   i) which variables to change/vary and how to change them,
   ii) which variables to control and how to control them, and
   iii) which variables to measure.
b) Decide how to measure data, including:
   i) how much data to collect (including number of trials, range of each variable, frequency/spacing of data collection) to obtain desirable uncertainty in measured values or calculated parameters,
   ii) what equipment to use, and
   iii) determine ways to reduce sources of uncertainty, systematics, or mistakes.
c) Make predictions about expected measurements, data, and results by:
   i) choosing a model to test from theory or predictions,
   ii) performing order of magnitude estimations,
   iii) checking units and dimensions,
   iv) consulting previous data and results, and/or
   v) collecting preliminary, pilot data.
d) Use the predictions about expected data, uncertainties, and systematics to:
   i) consider spacing and frequency of data,
   ii) quantify systematics or design tests to quantify them, and/or
   iii) identify where the main effect might be.

Objective 2: Evaluate the process and outcomes of an experiment

a) Analyze data using computational methods including (but not limited to) working with software such as spreadsheets, Matlab, or Python.
b) Decide how to analyze the quality of the measurements, which involves:
   i) identifying and distinguishing possible sources of uncertainty, either from the measurement model or physical model,
   ii) distinguishing instrumental uncertainty from random uncertainty,
   iii) determining how to quantify those sources of uncertainty (e.g. through standard deviation or standard uncertainty of the mean of repeated measurements or instrumental precision), and
   iv) propagating measurements uncertainties through calculations that use the measurements.
c) Compare pairs of measurements by determining the degree to which uncertain measurements are statistically distinguishable.
d) Describe how the least-squares method provides a measure of the best-fit (conceptual understanding).
e) Compare data to a model quantitatively by:
   i) plotting data and model on traditional x-y plots including appropriate representations of uncertainty,
   ii) linearizing data via semi-log or log-log plots,
   iii) performing linear and non-linear weighted least-squares fits,
   iv) plotting residuals, and/or
   v) interpreting the outcomes of the analyses.
f) Reflect (and respond appropriately) throughout the data collection process by:
   i) plotting as data are collected, and
   ii) evaluating the methods and data (e.g. checking uncertainty, systematics, or mistakes, monitoring constraints and feasibility, interpreting and making sense of results).

Objective 3: Extend the scope of an investigation

a) Draw inferences from analyses conducted (e.g. the degree to which data agree or disagree with a model or to other data).
b) When data and results do not come out as expected:
   i) Determine plausible explanations for the disagreement (e.g. assumptions or approximations in the models, measurement mistakes, or issues with equipment),
   ii) Test whether the results are repeatable or reproducible under the same conditions,

iii) Check whether the results are repeatable or reproducible with improved precision or measurement quality,
iv) Isolate and test components of the system (troubleshoot), and
v) Design new experiments/tests to explore other explanations for the disagreement.

c) When data and results do come out as expected:
   i) Test whether the results hold with higher levels of accuracy and precision (improve the quality of measurements), and/or
   ii) Extend the scope of the experiment to check if there is “new” physics at these levels.

Objective 4: Communicate the process and outcomes of an experiment

a) Describe the experimental goals, process, data, results, and conclusions in a lab notebook including:
   i) Justification for all decisions made, and
   ii) Supplementing, rather than replacing content when changes are made.
b) Use previous notes in their lab notebooks to inform design of future experiments.
c) Explain the experiment, broader context, and uniqueness of the investigation in a more formal format such as a final report, oral presentation, or poster.
d) Present conclusions, claims, and outcomes as arguments that are supported by and follow coherently from evidence (data).

Objective 5: Conduct an experiment collaboratively and ethically

a) Brainstorm with their group to construct a diverse set of ideas when making decisions.
b) Share experimentation responsibility with other group members (i.e. rotate roles, allow others to lead).
c) Provide positive and constructive feedback when evaluating peers’ work.
d) Consider issues of scientific ethics when analyzing data including:
   i) Dealing with outliers,
   ii) Dealing with data and results that do not match predictions or expectations, and
   iii) Dealing with data and results that do match predictions or expectations.