# Laboratory Manual

PHSC 12600 Matter, Energy, Space, & Time

The University of Chicago

Autumn 2020

# Labs

# LAB 1

# Force and Motion 1

## 1.1 Learning Goals

1. Frame your work in terms of the scientific cycle described.
2. Reflect on how your team worked together.
3. Observe, record, and represent different types of motion.
4. Develop a qualitative rule relating an object's change in motion to the unbalanced force exerted on it by other objects.
5. Represent your ideas in multiple ways to help understand what you are trying to describe.

## 1.2 The Scientific Cycle[1]

One way of describing science is the process of incrementally improving a shared model of how our universe works. In different fields of science, different methods and cycles are used, so there is no "One True Scientific Method." One can still create a model for the process of science, and we describe here one such cycle, summarized in Figure 1.1.

In this cycle, there are three types of experiments, each one representing a different stage of the scientific effort. One stage, often started when encountering a novel phenomenon, is the **observational experiment**. This is an experiment that consists of deciding what to observe and how to observe it, collecting data, finding a pattern, and brainstorming possible explanations for what is observed (also called "hypotheses").

Once one has some trial explanations, one can test one or more of those with a **testing experiment**. Here, one designs a new experimental procedure and uses each hypothesis to predict what will happen. Then the prediction is compared to the procedure's outcome. If they are different, then the hypothesis is judged to be not a helpful explanation for that phenomenon. If they are the same, then it is still helpful. Throughout this stage, one may make various assumptions that would need to be validated, as they can effect the prediction or outcome.

Once a hypothesis has been tested enough for people to find it useful, then it can be applied to solve practical problems, or to determine properties of particular situations, in an "application experiment."

[1] adapted from [1]

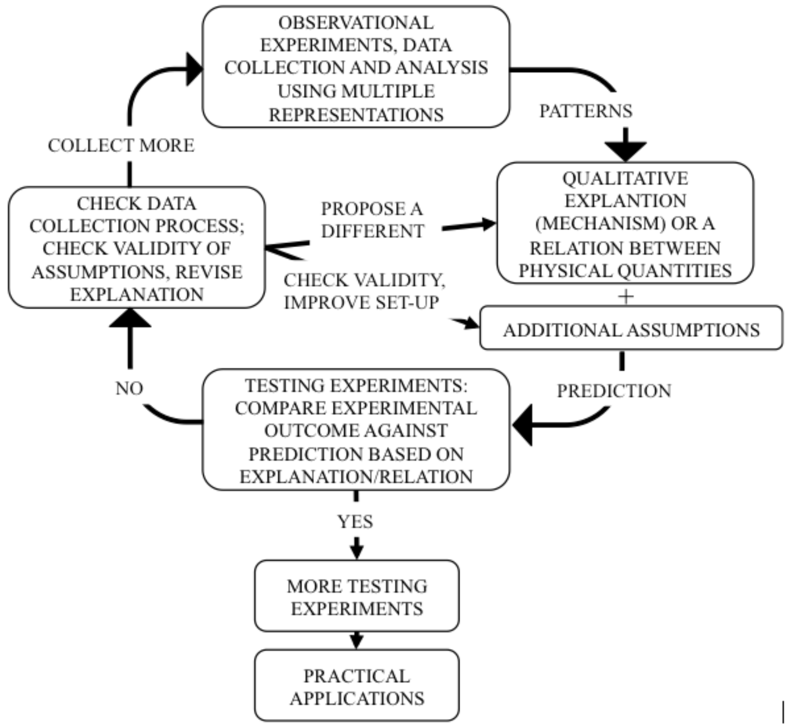


Figure 1.1: A model of the process some scientists go through to create knowledge.[2]

## 1.3 Team roles

**Decide on roles** for each group member. The available roles are:

- Facilitator: ensures time and group focus are efficiently used
- Scribe: ensures work is recorded
- Technician: oversees apparatus assembly, usage
- Skeptic: ensures group is questioning itself

these roles can (will?) rotate each lab, and you will report at the end of the lab report on how it went for each role. If you have fewer than 4 people in your group, then some members will be holding more than one role.

## 1.4 Observation Experiment: Recording and Representing Motion

**Goal:** Record the motion of an object and represent its motion using a motion diagram.

1. go to `https://physics.bu.edu/~duffy/HTML5/motion_diagrams.html`
2. click play, watch Cars 1 and 2 (represented by the top (red) and bottom (blue) big dots) drive forward.
3. notice that every second, a small dot is drawn to show where the car was at that time. this creates a visual record of the car's motion.

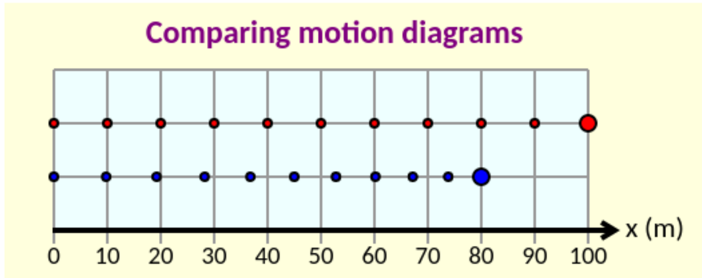


Figure 1.2: Motion diagrams of Car 1 (red, top) and Car 2 (blue, bottom). The small dots were marked every 1 second during the cars' motions.

4. How would you classify the object's motion: motion with constant rate, increasing rate, decreasing rate? Explain how you decided.
5. increase velocity of second car by dragging the velocity slider to the right.
6. record how the motion diagram changes.
7. imagine that you were given this plot without any velocity information - just the small dots. How could you tell which car was faster? Describe the procedure you would use to determine this.
8. Observe the motion diagram captured in Figure 1.2, specifically Car 2. How would you classify the object's motion: motion with constant rate, increasing rate, decreasing rate? Explain how you decided.

## 1.5 Observation Experiment: Forces Exerted on an Object by Other Objects

**Goal:** Learn to represent forces exerted on an object by other objects in a clear and efficient way.

**Available Equipment:** Two household objects of different weights and similar shapes, for example a bowling ball and a tennis ball.

Pick up a tennis ball and hold it stationary in your hand. Then pick up a bowling ball and hold it the same way. Do you feel any difference? Now we will learn to represent this difference graphically using force diagrams (sometimes called free-body diagrams).

**For each situation (tennis ball and bowling ball) do the following:**

9. List all the objects that interact with the ball. The ball is called the "object of interest" since that's what we are focusing our attention on. To interact with the ball, most other objects need to be in physical contact with it (the Earth is an exception — it can interact gravitationally from a distance).
10. Represent the ball with a dot and use an arrow to represent each interaction of another object with the ball. Connect the tails of the arrows to the dot. Label each force arrow with an $\vec{F}$ that has two subscripts. The first subscript represents the object that exerts the force on the object of interest; the second subscript represents the object of interest itself. For example, the force that the hand exerts on the ball can be written as $\vec{F}_{H\to B}$. Pay attention to the lengths of the arrows on each force diagram. Should any of them be longer or shorter than others?
11. Indicate what forces "cancel" or "balance" each other. Indicate if there is an "unbalanced" force. Explain how your force diagram is a better way of describing the forces being exerted on an object than written words.

12. Why are forces represented by arrows and not just by numbers or lines?

13. You can compare your force diagram to the one found at https://physics.bu.edu/~duffy/HTML5/force_motion_1D.html . Notice how the diagram changes when you change the mass.

## 1.6 Testing Experiment: Does an object's motion always occur in the direction of the unbalanced force exerted on it by other objects?

**Goal:** Test two ideas (also called *hypotheses*):

(a) An object always moves in the direction of the unbalanced force exerted on it by other objects.

(b) An object always changes its motion in the direction of the unbalanced force exerted on it by other objects.

**Available equipment:** Everything around you. You might be helped by things that roll, and forming a ramp with books. Also the following simulation: https://phet.colorado.edu/sims/html//forces-and-motion-basics/latest/forces-and-motion-basics_en.html (try the Motion screen in particular)

**Self-assessment:** To help you improve your scientific abilities, we provide you with self-assessment rubrics. A rubric is a method of aligning expectations for performance. Self-assessment is determining how well you performed a particular task. So, these self-assessment rubrics are designed to help you evaluate your performance while you are designing and performing your experiment.

The complete set of rubrics is available in Appendix B. In each lab, your report will be assessed using Rubric F, found in Table B.5, as well as 5 additional rubric rows listed in that lab. Each week, read through these and use them to evaluate your work as you design and perform the experiment. Your instructor will use the same rubrics to determine part of your grade for the lab. In particular, each row will be worth 3 possible points (from "Missing" being 0 points to "Adequate" being 3 points).

**Rubrics to focus on during this experiment:** C1, C2, C4, C7, C8. See Table B.3 for details.

14. First, think about the two competing ideas that you are testing. Think about how you can use the available equipment to design experiments relevant to both of them. Also, think what the words "test an idea" mean in real life. Does "testing" mean trying to support an idea or trying to disprove an idea? Which approach do you think is more productive? When you come up with at least 2 possible experiments, **contact an instructor or TA** and discuss your experiments with them.

15. After your discussion with the TA, record the two experiments you are going to perform. Draw pictures and force diagrams for each situation.

16. Make a prediction of the outcome of each experiment if idea (a) were correct.

17. Make a prediction of the outcome of each experiment if idea (b) were correct.

18. Make a table to record the following information for the object: (1) the direction of the motion, (2) the direction of the change in motion, and (3) the direction of the unbalanced force.

19. Perform each experiment and record the outcome in the table.

20. Decide if any of the predictions are consistent with the outcomes of the experiments.

21. Make a judgment about each idea. That is, decide which, if any, of the ideas are consistent with the outcome of the experiment. Remember, the goal of a testing experiment is to **disprove** ideas, not to support them.

22. Include arguments for why your judgments are reasonable in your report.

23. The experiment in Section 1.4 was called an observational experiment, and the experiment in this section was called a testing experiment. How do these names reflect the differences in performing these two kinds of experiments? (What aspects does one kind have that the other type does not?)

24. Design, describe, and (if possible) perform two more experiments in which the object does not move in the direction of the unbalanced force. Draw a motion diagram and a force diagram for each experiment.

25. You have represented motion and forces in different ways. Explain how these representations helped you to find a pattern/relationship between motion and forces.

## 1.7 Why Did We Do This Lab?

26. In a paragraph, summarize what you have learned during this first lab in terms of physics content and in terms of the purpose of the two kinds of experiments you designed and performed.

27. Describe how your understanding of the relationship between force and motion is different from your understanding before.

## 1.8 Group dynamics

28. Write a 100–200 word reflection on group dynamics and feedback on the lab manual. Address the following topics: who did what in the lab, how did you work together, what successes and challenges in group functioning did you have, and what would you keep and change about the lab write-up?

29. Write a paragraph reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps?

## 1.9 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, which apply just to that section, as well as F1 and F2, applied to the entire report), and 9 points for providing evidence in the lab report of completing all steps of the lab, including answering every question, for a total of 30 points.

LAB 2

# One-dimensional kinematics

## 2.1 Learning goals

1. Represent the motion of an object graphically, verbally, and mathematically. Change representations as required to describe your observations effectively.
2. Apply kinematics ideas to solve a practical problem.
3. Estimate experimental uncertainties in order to make judgments about experimental results.

## 2.2 Lab Team Roles

Decide which team members will hold each role this week: facilitator, scribe, technician, skeptic.

## 2.3 Observation Exp: Observe and represent motion

**Goal:** Represent the motion of an object graphically, translate between graphical and verbal representations, and change position, velocity, and acceleration consistent with those representations. This focuses on the part of the observation experiment that involves recording data.

**Available equipment:** Simulation found at https://physics.bu.edu/~duffy/HTML5/1Dmotion_graph_matching.html

1. Open the simulation at the address listed above. Notice that there is a position vs. time graph, a velocity vs. time graph, and a motion diagram.
2. For the following different situations, imagine that you are wearing a motion sensor and it will make a motion diagram as you walk, marking your position every second. For each way of walking described, adjust the initial position, velocity, and acceleration sliders to create the motion diagram that it would create. Each way of recording your observations is called a "representation". Construct an organized table similar to the one in Table 2.1 to record different representations.

   Try the following four experiments:

   a) Stand still, then walk forward at a steady pace, then stand still again.
   b) Walk backward at a steady pace.
   c) Walk forward at a steady pace for 4 seconds, then walk steadily but at a faster pace backward for the next 2 seconds.

| verbal description of experiment | motion diagram | graphs |
|---|---|---|
| Include where you start and end your motion, how you moved, and the time interval for which you moved | Remember to include dots and the number line. | position-vs-time and velocity-vs-time |

Table 2.1: Format for table of representations.

d) Walk forward at a steady pace for 2 seconds, then continually increase your speed.

3. A fellow student, Alex, does not understand why it is a good idea to represent the same information in these three different ways (verbal, motion diagrams, graphs). What do you say to Alex to help them understand the use in doing this?

4. What was the purpose of this first experiment? Specifically what did you learn? How did you learn it?

## 2.4 Testing exp: Do you understand graphs?

**Goal:** Adjust the simulation parameters in such a way that the graphs produced by your imagined motion match a few pre-determined graphs.

**Available equipment:** Simulation found at https://physics.bu.edu/~duffy/HTML5/1Dmotion_graph_matching.html

5. Open the simulation at the address listed above. Notice the buttons for Graph 1 through Graph 10.

6. Pick three of the position graphs (Graphs 1–5) and three of the velocity graphs (Graphs 6–10) to match.

7. Do the following for each:

   a) Before you proceed to perform the experiment, you need to decide how you will move the sliders. Predict, based on your observations from the first experiment and your knowledge of kinematics, how you should move to produce graphs that match those that are on the screen. **Record your predictions.**

   b) After you have made your prediction, perform the experiment by adjusting the position, velocity, and acceleration sliders and using the play and pause buttons. **Record the outcome graph.**

   c) If the graph produced by your motion did not match the provided graphs, **discuss in your report** possible reasons and how you would move differently to make the motion match the graph more closely.

   d) Where on the graph is the position of the object represented? Where is the time represented?

8. How do motions that are represented by $x(t)$ lines with various slopes differ from each other? What information can we obtain from the slope of an $x(t)$ graph?

## 2.5 Application experiment: how long is the brick?

- **Goal:** Determine the length of a brick in a mechanics simulation.

- **Available equipment:** Stopwatch (app, website, watch, etc.), simulation at https://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html
- **Rubrics to focus on:** D2, D4, G1, G2, G4
- Since this is the first application experiment we've done, read through the application experiment rubric, D. Rubric G is also important, as it is about data analysis, and this is a quantitative experiment.
- For comparing two values with uncertainties, to see if they are the "same" or not, see Appendix A.3.

9. Open the simulation in the link above and go to the section marked "Motion". Notice that you can select different view options in the upper right hand corner.
10. Brainstorm two *independent* experiments to determine the length of the brick. One of the ways must use the formula that describes the relationship between displacement $\Delta x$, velocity $v$, and time $t$ during constant velocity,
$$\Delta x = vt\,. \tag{2.1}$$
Another way could involve the typical size of other objects in the simulation.
11. When you come up with at least 2 possible experiments, **contact an instructor or TA** and discuss your experiments with them.
12. For each experiment you conduct, including the following in your report:
    a) Describe your experimental procedure. Include a sketch of your experimental design.
    b) List the sources of experimental uncertainty.
    c) Explain what steps you will take to minimize experimental uncertainty.
    d) Perform the experiment. Record the data using appropriate representations (motion diagrams, tables, graphs, etc.). Determine the uncertainty in the measurements you made (you will need to do multiple trials to do this).
    e) Use your measurements and their uncertainties to determine the length of the brick. Propagate uncertainties through your calculations as described in Appendix A.2.
    f) Report your result as a value plus or minus the uncertainty (e.g. $5 \pm 1$ m).
13. Compare the two values you obtained for the brick length using the method described in Appendix A.3 and obtain a $t'$ value.
14. Taking into account experimental uncertainties and the assumptions you made, decide if these two values are consistent or not. If they are not consistent, explain possible reasons for how this could have happened (for example, assumptions made, underestimating uncertainty).
15. Decide on a final value (including uncertainty of that value) for the brick length based on the results of your experiments.
16. Describe the shortcomings you noticed in the experiments. Suggest specific improvements.

## 2.6 Why did we do this lab?

17. Explain how each of the group member's understanding of representations of motion is different now compared to before the lab.
18. In this lab you conducted an observation experiment and an application experiment. How are the purposes of an observation experiment and an application experiment different?
19. In your own words, what is it meant by "experimental uncertainty"? Why should we care about it?
20. Give real-life examples of instances when people need to collect and analyze quantitative data (numbers with units) to describe and understand what is happening.

## 2.7 Group dynamics

21. Write a 100–200 word reflection on group dynamics and feedback on the lab manual. Address the following topics: who did what in the lab, how did you work together, what successes and challenges in group functioning did you have, and what would you keep and change about the lab write-up?
22. Write a paragraph reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps?

## 2.8 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, which apply just to that section, as well as F1 and F2, applied to the entire report), and 9 points for providing evidence in the lab report of completing all steps of the lab, including answering every question, for a total of 30 points.

LAB 3

# Force and Motion 2

## 3.1 Learning Goals

- Make careful observations and find quantitative patterns.
- Choose and fit models to data in order to describe a pattern.
- Test a hypothesis quantitatively.

## 3.2 Lab Team Roles

Decide which team members will hold each role this week: facilitator, scribe, technician, skeptic. If there are three members, consider having the technician and skeptic roles be held by one person.

## 3.3 Observation experiment: how fast and how far does force get you?

**Goal:** Your friend Taylor noticed that when they pushed on a skateboard, it started going faster. They started wondering — how does force and mass affect how far an object goes and how fast it gets? Investigate this and find some quantitative patterns. Represent the patterns in graphical and formula form.

**Available equipment:** Force and Motion Basics simulation (`https://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html`)

**Rubric rows to focus on:** B1, B3, B5, B7, B8 (and F1 and F2 for all sections, like normal)

1. read through the rubric B to see the steps to follow and what to ensure you include, given the rubric rows listed above.
2. Taylor's description of what to look at might not be specific enough for you. They're not answering your texts about it, so you'll need to decide what specific phenomenon to investigate. Discuss and brainstorm experiments with your group (and play with the sim), then discuss with a TA or instructor. (There are several different phenomena you can choose. There is not a right one we are looking for)
3. Design and record your experimental setup and procedure, including a diagram of the setup.
4. What quantities are you measuring, in particular? And which are the independent and dependent variables?

5. Describe in detail how you are making the measurements.

6. Conduct your experiment and record your data. Express in a table or graph form.

7. Identify a pattern in the data. Your resulting pattern should be described precisely in words, and in an equation that describes how the dependent variable changes in response to a change in the independent variable(s).

8. You may find it useful in this experiment or future ones to fit a test function to data. This is called curve fitting. You can use your preferred curve fitting program, or use SciDaVis, a free open source graphical analysis program.

   - You can download and install it on your computer from https://sourceforge.net/projects/scidavis/files/SciDAVis/1/1.26/.

> **Mac users:** if you get an error when trying to run SciDaVis, saying that it is from an unidentified developer, follow the directions at the following website to let it run:
> https://support.apple.com/guide/mac-help/open-a-mac-app-from-an-unidentified-developer-mh
> 10.15/mac/10.15

   - Optionally, watch the short video tutorial from the Lab Module on Canvas, describing how to enter data into SciDAVis and create a curve fit.
   - In SciDAVis X is the independent variable and Y is the dependent variable.
   - To plot the data, Highlight the data X,Y, and/or yEr you want to plot (by clicking the X column, holding the Ctrl key, then clicking the Y column). Then click Plot ⇒ Scatter. Clicking on the axis, curves, axis titles, or data points allows you to customize your graph.
   - To fit an equation to the data, first enter the data, then save the project, so you won't accidentally lose your work. Then, select Analysis ▸ Fit Wizard... from the drop-down menu. Type your desired equation into the large box. You can use any of the functions you can find in the lists at the top of the window and combine them how you would like. For fit parameters, use the letters a, b, c, and so on. For each fit parameter you use, include it in the list of parameters. For example, if you think the data are best represented by a tangent function, you could type "`b*tan(c*x+d)`" in the box. Then click the "Fit >>" button. A new screen will come up. Enter your initial guesses for the parameters. Also enter the high and low range for X. Then the "Fit" button to fit the data with this equation. This finds the parameters for the equation that make it best fit the data. The values for the fit and their uncertainties will be displayed in the Results log. Experiment to find an equation that seems to fit well.

## 3.4 Testing experiment: displacement and time under constant acceleration

**Goal:** Taylor performed their own observation experiment and arrived at the following mathematical description for the displacement $x$ of an object of mass $m$ subject to a constant force $F$ for a duration $t$, starting from rest:

$$x = \frac{Ft^2}{m}\,. \tag{3.1}$$

Taylor would like you to verify this. I, the lab manual, would like to show you one way of using curve fitting to test it.

**Available equipment:** Force and Motion Basics simulation (https://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html)

**The idea** is to produce a number of $(t, x)$ data points from an object of known mass, subject to a constant force and plot them (time on the horizontal axis and displacement on the vertical axis). Then fit a quadratic function to those points, of the form $Y = C * X^2$. The curve fit will produce the best fit parameter $C \pm \delta C$. In this situation, the hypothesis predicts that $C = F/m$. Comparing the values using their uncertainties, the prediction will match the outcome if the $t'$ statistic is less than 1.

9. Discuss what experimental procedure to use to collect the data using the sim. How many data points do you need? How will you determine the uncertainty of each data point? What will you use to take the measurements and what role will each person take in the experimental procedure? *Hint: if things are happening too quickly to record, you can take a video and then pause as needed during playback.*

10. Write down your procedure and draw a sketch to describe the setup.

11. Conduct the data collection, including uncertainty estimation for each point.

12. Execute the data analysis as described above. **Record the graph and best fit parameters with their uncertainties.**

13. Calculate the $t'$ statistic and use it to decide if the outcome matches the prediction.

14. Based on this experiment, what would you say to Taylor about their hypothesis?

## 3.5 Application experiment: mass of the mystery box

**Goal:** Use the pattern you discovered in Section 3.3 to find the mass of the mystery box in the Force and Motion Basics simulation.

**Available equipment:** Force and Motion Basics simulation (`https://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html`)

15. Design and conduct the experiment. Include a description and sketch of the setup and procedure, data table, uncertainty analysis, and final determination of the box's mass.

    If you are unable to use the pattern you discovered to solve the problem, and your TA agrees, then you can use results from Newtonian mechanics, for example $F = ma$ and $a = \frac{v_f - v_i}{t}$ , where $a$ is the acceleration, $v_f$ is the final velocity, and $v_i$ is the initial velocity.

## 3.6 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, which apply just to that section, as well as F1 and F2, applied to the entire report), and 9 points for providing evidence in the lab report of completing all steps of the lab, including answering every question, for a total of 30 points.

LAB 4

# Energy Conservation

## 4.1 Learning goals

- Use energy conservation to discover relationships between kinematics and types of energy.
- Use energy conservation to solve a problem.
- Identify assumptions made during an experiment and how they might affect the results.
- Take video and analyze motion using video tracking software.

## 4.2 Lab Team Roles

Decide which team members will hold each role this week: facilitator, scribe, technician, skeptic. If there are three members, consider having the skeptic double with another role. Consider taking on a role you are less comfortable with, to gain experience and more comfort in that role.

Additionally, if you are finding the lab roles more restrictive than helpful, you can decide to co-hold some or all roles, or thinking of them more like functions that every team needs to carry out, and then reflecting on how the team executed each function.

## 4.3 Energy

Energy can be defined in several different ways. One way that is useful for this lab is that energy is the ability to do work — that is, the ability a system has to change its environment. One way it has the ability to do this is by nature of its speed. If an object is traveling relative to its surroundings, it can run into things and affect them. This type of energy is called *kinetic energy*. Another way an object has this ability to affect things is through its position. These ways are called *potential energy*. Either being further away from massive objects (gravitational potential energy), being confined to stay near other atoms (chemical), or confined within an atomic nucleus (nuclear).

Energy can be transformed into different types, and is conserved throughout interactions. That is, accounting for all forms of energy transformations, the amount of energy before an interaction is always equal to the amount after. An intuitive analogy is given with mass conservation: if I have 2 kg of pebbles in one hand, and I move 1 kg of them to my other hand, then you can be confident that 1 kg remains behind, unless mass is being converted into other forms of energy.

The law of energy conservation is a powerful tool in physics, allowing for discoveries: for example, in radioactive beta decay, an electron is released from an atomic nucleus with a certain amount of kinetic energy. This energy varies, but physicists had found that all the energies after the decay did not add up to the energy beforehand. They theorized and later discovered that this was due to a then-undiscovered particle, the neutrino.

### Qualitative derivation of gravitational potential energy

One type of energy was stated to be gravitational potential energy (call it $U_{\text{grav}}$), the energy gained by being further away from other massive objects. Near the Earth's surface, you can investigate this on a qualitative level easily — if you lift a book a little bit off the ground, $h_1$, and drop it on your foot, it falls back down and doesn't do much damage. If you lift it high off the ground, up to $h_2$, and drop it on your foot, it will hurt more and cause more damage. More ability to affect the environment, and thus more gravitational potential energy. So we have already discovered that with more height off the ground, there is more $U_{\text{grav}}$. Further, if you set your foot on a chair of height $h_1$, and raise the book the same height $h_1$ above your foot as you did in the first case above, then you would receive the same damage. So raising the book from 0 to $h_1$ increased the book's $U_{\text{grav}}$ the same amount as raising from $h_1$ to $2h_1$. One can infer from this that $U_{\text{grav}}$ is proportional to the height raised, or $U_{\text{grav}} \propto h$.

## 4.4 Observation experiment: How is kinetic energy related to velocity?

Now that you know how gravitational potential energy depends on height (at least near the Earth's surface), you might be tempted to study falling objects more. As objects fall, they pick up speed, and thus kinetic energy.

### Goal

Use the law of energy conservation and the theory that $U_{\text{grav}} \propto h$ to determine how kinetic energy $E_{\text{k}}$ and velocity $v$ are related, using videos of falling objects that you take and analyze.

### Available equipment

- a small, dense, durable object to drop on the ground
- a video camera like one on a smartphone or your webcam
- the software Open Source Physics Tracker

### Rubrics to be assessed in this experiment

B3, B7, B8, G4, G5

### Steps

1. Discuss your experimental setup and procedure, including analysis, with your group. How will you measure kinetic energy (directly or indirectly), how will you measure velocity, and what will you vary in order to change one of them to find a pattern?
2. Record clearly the phenomenon you are investigating.
3. Decide what physical quantities are to be measured and identify independent and dependent variables.
4. Record a detailed description of what measurements you are making and how you will make them.
5. Carry out your measurement plan, using the following guide for video analysis using Tracker.

### Record the video

6. Find a good object to drop. It should be dense enough to not be slowed down significantly by air resistance.

7. Using the camera on one of your group member's phones, record a video of the object falling.

   Here are some tips to get a quality video:

   - Include an object of known length in the shot, at the same distance from the camera as the falling object. This gives a reference length, so that you can find how each camera pixel scales to the physical situation.
   - Avoid parallax error by having the object be at about the same distance from the camera throughout the fall. Having the camera be farther away can help. Also, you can ensure that the top and the bottom of the fall are the same distance from the camera.
   - Hold the camera steady.

8. Record that video and transfer the video to a computer that has Tracker installed.

### Importing the data into Tracker

In this part, you'll use Tracker to record the position of the object at each timestep. To do this, you'll need to tell it what direction "down" is in, what the scale of the image is, and when time $t = 0$ is. Then you'll record the position of the object in every frame, and you'll plot velocity vs. time to find the velocity just before the object hit the floor.

9. Open Tracker on a computer. You can install it on your own computer by visiting `https://physlets.org/tracker`.

10. Optionally, watch this 3-minute tutorial on how to use Tracker: `https://www.youtube.com/watch?v=n4Eqy60yYUY`

11. In Tracker, open your video.

12. **Find frame when zero time is.** Move the slider below the video to the right to advance the frames until you find the first one in which the object is falling. Record that start frame number, which is found to the left of the slider bar in red.

13. **Find the last relevant frame.** Keep moving the slider to the right until you find the last frame before the object hits the floor. Record that end frame number.

14. To **tell Tracker about these frames**, click the 5th icon from the left on the toolbar above the video ("Clip settings") and enter the start frame and end frame.

15. **Tell Tracker how long things are.** In astronomy applications, this is known as the "pixel scale". Here we can just draw a line on the frame and tell Tracker how long that line is in real life. Click the 6th icon from the left (blue, with a "10") and select `New` → `Calibration Stick`. Shift-click to mark each end of your known length, and type in your known length, with units in the box that appears along the stick. Use "m" for meters.

16. **Align the coordinate system.** In the toolbar, click the 7th icon from the left (magenta crossed lines). Click and drag the coordinate system's origin (the intersection of long lines) to the location of the object in the start frame.

17. **Check to see if the camera was tilted.** Advance the video to see if the object moves along an axis. If it goes off at an angle, the camera was tilted compared to the direction of motion. In this case, rotate the coordinate system to align with the motion by clicking and dragging the small line that crosses one of the axes.

 

18. **Tell Tracker where the object is in every frame.**
    a) In the toolbar, click `Create` → `Point Mass`.
    b) Ensure the slider is at the start frame.
    c) Shift-click on the object. Notice that the frame advances to the next one automatically.
    d) Continue to shift-click to mark the object's position throughout the duration.

**Analysis**

19. **Ensure the correct axis is selected for analysis.** Look at the plot to the right of the video. If there is not a smooth-ish curved line, click on the axis label "x (m)" and choose instead "y (m)".
20. To view the velocity graph, click on the vertical axis label on the plot to the right of the video and select vx or vy.
21. Find the velocity that is relevant to your measurement plan and record it.
22. Once you have a table of data that you can use to search for a pattern, copy it into SciDAVis and try different functions to see what pattern fits.
23. Identify the pattern in words and record a mathematical expression (formula) that represents the pattern you found, with a discussion of how well your expression agrees with the data.

## 4.5 Application experiment: finding energy lost to drag

### Goal

Assuming that $U_{\text{grav}} = Agh$ and $E_{\text{k}} = \frac{A}{2}v^2$, where $g = 9.8\,\text{m/s}^2$ and $A$ is the same unknown constant in both equations, find the fraction of energy converted to thermal energy via air resistance, for a light falling object.

### Available equipment

- a light object to drop on the ground like gently crumpled paper or a coffee filter
- a video camera like one on a smartphone
- the software Open Source Physics Tracker

### Steps

24. Follow the steps listed in Rubric D (Table B.4) to find the fraction of energy transformed into thermal energy. You do not need to do two independent methods as described in D5.

## 4.6 Group dynamics

25. Write a 100–200 word reflection on group dynamics and feedback on the lab manual. Address the following topics: who did what in the lab, how did you work together, what successes and challenges in group functioning did you have, and what would you keep and change about the lab write-up?
26. Write a paragraph reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps?

## 4.7 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, which apply just to that section, as well as F1 and F2, applied to the entire report), and 9 points for providing evidence in the lab report of completing all steps of the lab, including answering every question, for a total of 30 points.

LAB 5

# Is light a particle or a wave?

You may have heard that light is both a particle and a wave, and that this is paradoxical. We want you to get a clear sense of why physicists have come to this wild conclusion, and continue to practice working with the scientific cycle that we have presented.

## 5.1 Learning goals

- Make careful predictions based on hypotheses and a given experimental setup.
- Gain a clear sense of how light behaves like a particle, and how it behaves like a wave.

## 5.2 Lab Team Roles

Decide which team members will hold each role this week: facilitator, scribe, technician, skeptic. If there are three members, consider having the skeptic double with another role. Consider taking on a role you are less comfortable with, to gain experience and more comfort in that role.

Additionally, if you are finding the lab roles more restrictive than helpful, you can decide to co-hold some or all roles, or thinking of them more like functions that every team needs to carry out, and then reflecting on how the team executed each function.

## 5.3 Observation experiment: describing waves and particles

In order to make predictions in the testing experiments with light, it will be helpful to determine what properties waves and particles have in more obvious situations, so that these properties can be applied to less obvious situations with light.

### Goal

Describe patterns of behavior of waves and particles that can be used to differentiate between them.

### Available equipment (simulated)

- Particle box: box where particles move towards each other and interact (Simulation: https://phet.colorado.edu/sims/html/collision-lab/latest/collision-lab_all.html (Select "Explore 2D"))

- Ripple tank: tank of shallow water with set of plungers (to create waves) and walls that obstruct the path of waves (Simulation: http://www.falstad.com/ripple/)
- String attached to an oscillator (Simulation: https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html)

**What happens when their paths intersect?**

1. In the particle box, **observe and record** what happens when the two particles approach each other and interact. How are their motions different after the interaction?
2. In the ripple tank, watch the wave crests (light color) expand away from the source, a plunger pushing down and up in the water.
3. Click anywhere in the tank to touch your finger into the water momentarily and create a ripple (a single wave crest). **Observe and record** what happens when the ripple approaches each wave crest and interacts. How are the ripple and wave motions different after the interaction?
4. Summarize the difference between particles and waves in this case.

**How do they deliver energy?**

5. With the wave on a string simulation, click "loose end" on the right side, then click and drag the wrench to see how it moves the string.
6. Select "Oscillate" on the left side of the screen. Reduce the amplitude to about 0.2 cm. Reduce the frequency to exactly 1.47 Hz. Reduce the damping to "None".
7. Press "Restart" to reset the string to neutral.
8. Watch what happens as the wave delivers energy to the ring at the right. Does the wave deliver energy continuously or in short bursts? Is there a minimum amplitude needed to start the ring in motion?
9. In contrast to this, consider the following example of particles: imagine that you have a bag of basketballs and a friend is sitting on a chair on wheels, which is resting on a carpet. If you toss the ball gently to them, they don't budge at all. But if you toss a ball fast enough, it pushes them back. Does this deliver energy continuously or in short bursts? And if you keep tossing balls gently to them, will that ever get them moving?
10. Summarize the difference between particles and waves in this case.

## 5.4 Testing experiment: is light a particle or wave?

### Goal

For the two situations below (light incident on metal and light incident on slits), test the following hypotheses:

(A) Light is made of particles.

(B) Light is made of waves.

### Rubrics to be assessed

C2, C4, C7, C8, G4

## Situation 1: light shining on metal

### Assumptions

- Light travels with different wavelengths.
- Light with a shorter wavelength (higher frequency) carries more energy.
- Metals have particles called "electrons" in them that can absorb energy from light. Once an electron absorbs a certain amount of energy, it is emitted from the metal and gains kinetic energy.

### Available equipment (simulated)

The following equipment is available as a simulation here: https://phet.colorado.edu/en/simulation/legacy/photoelectric

- An evacuated glass tube, inside of which are two metal plates connected by a conducting wire.
- A lamp that can emit light at different, controllable wavelengths and at different, controllable intensities, aimed at only the left plate
- A method of seeing electrons that are floating inside the tube (in real life these are not directly visible)
- A method of measuring the electric current produced in the wire (electric current is proportional to the number of electrons arriving at the right plate per second)

### Steps

11. Before turning on the lamp, determine what each hypothesis (A) and (B) predicts will happen when the wavelength and intensity are varied. **Record the two predictions.**
12. Develop an experimental procedure that will allow you to collect the data you need to compare to the predictions. **Record this procedure.**
13. Collect and record your relevant data.
14. Compare the experimental outcome to the predictions and determine which, if any, of the predictions agree with the outcome, and to what degree.

## Situation 2: light shining on two small slits

Consider the situation in Figure 5.1.

15. Determine what each hypothesis (A) and (B) predicts the screen will look like. Where are the dark and bright regions?
16. Ask your TA for the experimental result that was done using a red laser.
17. Compare the experimental outcome to the predictions and determine which, if any, of the predictions agree with the outcome, and to what degree.

## Conclusion

18. Given the results from Situations 1 and 2 above, what judgment can you make about the hypotheses?

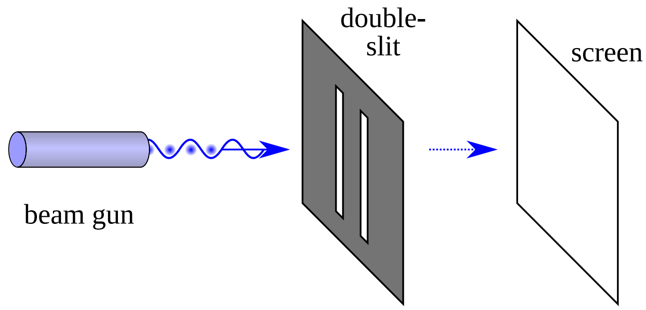


Figure 5.1: Experimental setup. Note that the light emitted from the beam gun (or laser) is broad enough to go through both slits.

## 5.5 Group dynamics

19. Write a 100–200 word reflection on group dynamics and feedback on the lab manual. Address the following topics: who did what in the lab, how did you work together, what successes and challenges in group functioning did you have, and what would you keep and change about the lab write-up?

20. Write a paragraph reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps?

## 5.6 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, which apply just to that section, as well as F1 and F2, applied to the entire report), and 9 points for providing evidence in the lab report of completing all steps of the lab, including answering every question, for a total of 30 points.

LAB 6

# Discovering the Hydrogen Atom

## 6.1 Learning Goals

- Critically evaluate model of physical phenomena and understand how these models are formulated.
- Develop methods for testing and working with objects which cannot be directly observed.
- Understand the atomic model and why it differs from what classical physics predicts.

## 6.2 Lab Team Roles

Decide which team members will hold each role this week: facilitator, scribe, technician, skeptic. If there are three members, consider having the skeptic double with another role. Consider taking on a role you are less comfortable with, to gain experience and more comfort in that role.

Additionally, if you are finding the lab roles more restrictive than helpful, you can decide to co-hold some or all roles, or thinking of them more like functions that every team needs to carry out, and then reflecting on how the team executed each function.

## 6.3 Model Evaluation and Construction

When thinking of an atom, we usually tend to imagine a series of electrons orbiting around a nucleus in nice circular orbits — this is the planetary model of the atom.While at first this model might seem unremarkable, the reality is that the physics that describes it is a lot weirder than you think!

### Goal

Analyze the planetary model using classical physics concepts, determine its shortcomings, and begin to develop your own model of the atom.

### Steps

1. First, let's take the classical planetary model of the atom at face value. Using only classical physics concepts, find what's wrong with this model. Take the system of the electron orbiting the nucleus to be equivalent to that of a satellite orbiting the Earth.
   - Think first about what happens to a satellite orbiting Earth as it interacts with the atmosphere. What forces are acting on it? What happens to it over time?

- Consider that changing the orbital radius of a body requires a corresponding change in energy. Think about the changes in kinetic and potential energy as the satellite moves closer or farther from the Earth.

2. Once your group has come up with an answer, describe what happens to the orbiting object in terms of its energy and its position over time. What implications does this have when you apply it to the atom? **Write down your explanation**

3. After identifying the problem with the model, develop 2 or 3 ideas for a new model which solves the issues you found. **Forget any previous knowledge of the atom. Think outside the box. Write down your ideas and describe how they solve the problem.**

   - These models don't have to be too complicated, just try thinking of different ways in which the electron might move or behave in relation to the nucleus.

## 6.4 Testing and Observation: How does an atom absorb and release energy?

Now that you have a rough model of the atom, lets supplement that with some observations to see if you can make it more robust. The difficulty with trying to learn about the structure of the atom is that we have no way of directly observing it. However, we are able to interact with it and observe the results.

### Goal

Fire photons at a hydrogen atom, determine it interacts with light energy, and modify your model based on your observations.

### Available Equipment

- PHET Models of the Hydrogen Atom Lab: https://phet.colorado.edu/en/simulation/legacy/hydrogen-atom

### Rubrics to be assessed

B5, B7, B9, C4, C5

### Steps

4. Once in the simulation, make sure to turn on the spectrometer, and familiarize yourself with the tools available. Available to you are photon gun which can be set to white or monochromatic (single color) light, a spectrometer which you can take snapshots of, and a speed toggle.

5. This simulation is meant to demonstrate how an atom absorbs and emits energy in the form of photons of light. Based on this, what predictions, if any, does your model make? **Record your model's predictions.**

6. Fire white light at the atom. What patterns do you observe? Record any qualitative observations and describe the pattern.

7. Turn off the light, reset the spectrometer, and switch over to monochromatic light. Fire light of several different wavelengths (colors) at the atom. **Record your observations.**

8. Now, for each of the wavelengths listed, record what happens when photons at that wavelength are fired at the atom. Describe any patterns you observe and include screenshots of the spectrometer. (Pay attention to the order in which the photons are emitted)

- Wavelengths to test: 122nm, 103nm, 97nm, 95nm, 94nm
- **Important: Sometimes the simulation might freeze and the atom will appear to no longer emit photons. If that happens, switch over to the white light setting, wait until the atom starts emitting again, switch over to monochromatic light, reset the spectrometer, and continue.**

9. One thing you might have noticed is that for certain wavelengths, the atom might emit several different colors of light. Why might this be happening? Think about it in terms of the energy being absorbed and emitted by the atom. Does it make sense for the atom to be emitting photons at higher wavelengths than the ones absorbed? Remember that energy is inversely proportional to the wavelength of the photon (as one increases the other decreases). Why does the atom absorb at some wavelengths and not others? **Record your answers to these questions.**

10. Once you believe you have found a pattern, modify your model of the atom so that it is able to explain these new observations. Record any changes you made and describe how these explain the observed patterns.

    - Think about where the energy goes in the atom once the photon is absorbed.
    - Does your atom somehow change following an increase in energy? It might help to think back to the classical orbit analogy used in the previous experiment.
    - How does your model account for the fact that only very specific amounts of energy are absorbed and emitted?

## 6.5 Model Evaluation

### The Building Blocks of Everything

The word atom finds its roots in the Greek word *atomos* which means indivisible and is believed to have first been used by Democritus to refer to the indivisible spheres which he believed to be the building blocks of our world. Today, we have a far better understanding of the atom and its structure. However, this is information we take for granted. For millennia, there was no clear answer as to what the smallest unit of everything was, and only relatively recently did we develop tools which allowed us to study them more closely. The first comprehensive atomic model was developed in 1803 by John Dalton, who thought of them as solid spheres which changed depending on the element they made up. Then, in 1904, JJ Thompson developed the "Plum Pudding" model, which proposed that the atom as made up of electrons floating within a cloud of positive charge. Then in 1911 Ernst Rutherford proposed the nuclear model, where the positive charge was concentrated in the center of the atom. Two years later, Niels Bohr improved upon Thompson's model, suggesting that the orbits were fixed. Finally, Erwin Schrodinger proposed in 1926 the quantum model, where electrons exist around the nucleus in a "cloud of probability". You will now have a chance to interact with each of these models.

### Goal

Evaluate each model and try to develop an understanding for the reasoning behind it. You will also quantify the energy interactions in an atom, and see how the principle of conservation of energy is maintained.

### Available Equipment

- PHET Models of the Hydrogen Atom Lab: https://phet.colorado.edu/en/simulation/legacy/hydrogen-atom

### Steps

11. Make sure the simulation is in "Prediction" mode. On the left, you will see a list of all the atomic models organized from "classical" to "quantum".

12. For each model:

    - Provide a qualitative description of its structure and behavior. How does it absorb energy? Where does it go once it's absorbed? Are there any structural changes? etc.
    - Along with each description, provide an explanation of the possible reasoning behind each model. What problems does each model address? Why would each model be a good guess as to the structure of an atom? Likewise describe the limitations of each model, if anything. What does it fail to describe or account for?
    - Now compare the model you came up with to some of the other models. Does it resemble any of the other models? Does it improve on some of the shortcomings of the other models? What did you take into account that they did not? Was there anything missing from your model? What did you fail to consider? **Write down your observations.**
    - **Along with each description, include a screenshot of the spectrometer for the model.**

13. In the previous experiment, you saw how atoms can only absorb and emit a very specific amount of energy. Using the Bohr model, calculate the energy being emitted by the atom when it absorbs light with wavelength $\lambda = 94$nm.

    - Use the equation $E = h\nu$, where $E$ is energy (SI unit is the joule (J)), $h$ is the Planck constant equal to $6.62 \times 10^{-34}$ J s, and $\nu$ (Greek letter pronounced like "new") is the frequency of the emitted photon (SI unit is hertz (Hz), or $s^{-1}$).
    - To convert from wavelength to frequency use the equation $\nu = \dfrac{c}{\lambda}$.
    - Make sure to include uncertainties in your calculations.
    - How does the total emitted energy compare to the energy absorbed? Are they equal?

14. Sometimes, you might see that the atom emits light at 656nm (red light). Why might the atom emit but not absorb light at that same wavelength? **Write down your answers**

## 6.6 Group dynamics

15. Write a 100–200 word reflection on group dynamics and feedback on the lab manual. Address the following topics: who did what in the lab, how did you work together, what successes and challenges in group functioning did you have, and what would you keep and change about the lab write-up?

16. Write a paragraph reporting back from each of the four roles: facilitator, scribe, technician, skeptic. Where did you see each function happening during this lab, and where did you see gaps?

## 6.7 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, which apply just to that section, as well as F1 and F2, applied to the entire report), and 9 points for providing evidence in the lab report of completing all steps of the lab, including answering every question, for a total of 30 points.

APPENDIX A

# Analysis of Uncertainty

A physical quantity consists of a value, unit, and uncertainty. For example, "$5 \pm 1\,\mathrm{m}$" means that the writer believes the true value of the quantity to most likely lie within 4 and 6 meters[1]. Without knowing the uncertainty of a value, the quantity is next to useless. For example, in our daily lives, we use an implied uncertainty. If I say that we should meet at around 5:00 pm, and I arrive at 5:05 pm, you will probably consider that within the range that you would expect. Perhaps your implied uncertainty is plus or minus 15 minutes. On the other hand, if I said that we would meet at 5:07 pm, then if I arrive at 5:10 pm, you might be confused, since the implied uncertainty of that time value is more like 1 minute.

Scientists use the mathematics of probability and statistics, along with some intuition, to be precise and clear when talking about uncertainty, and it is vital to understand and report the uncertainty of quantitative results that we present.

## A.1 Types of measurement uncertainty

For simplicity, we limit ourselves to the consideration of two types of uncertainty in this lab course, instrumental and random uncertainty.

### Instrumental uncertainties

Every measuring instrument has an inherent uncertainty that is determined by the precision of the instrument. Usually this value is taken as a half of the smallest increment of the instrument's scale. For example, 0.5 mm is the precision of a standard metric ruler; 0.5 s is the precision of a watch, etc. For electronic digital displays, the equipment's manual often gives the instrument's resolution, which may be larger than that given by the rule above.

Instrumental uncertainties are the easiest ones to estimate, but they are not the only source of the uncertainty in your measured value. You must be a skillful experimentalist to get rid of all other sources of uncertainty so that all that is left is instrumental uncertainty.

[1] The phrase "most likely" can mean different things depending on who is writing. If a physicist gives the value and does not given a further explanation, we can assume that they mean that the measurements are randomly distributed according to a normal distribution around the value given, with a standard deviation of the uncertainty given. So if one were to make the same measurement again, the author believes it has a 68% chance of falling within the range given. Disciplines other than physics may intend the uncertainty to be 2 standard deviations.

### Random uncertainties

Very often when you measure the same physical quantity multiple times, you can get different results each time you measure it. That happens because different uncontrollable factors affect your results randomly. This type of uncertainty, random uncertainty, can be estimated only by repeating the same measurement several times. For example if you measure the distance from a cannon to the place where the fired cannonball hits the ground, you could get different distances every time you repeat the same experiment.

For example, say you took three measurements and obtained 55.7, 49.0, 52.5, 42.4, and 60.2 meters. We can quantify the variation in these measurements by finding their standard deviation using a calculator, spreadsheet, or the formula (assuming the data distributed according to a normal distribution)

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

where $\{x_1, x_2, \ldots, x_N\}$ are the measured values, $\bar{x}$ is the mean of those values, and $N$ is the number of measurements. For our example, the resulting standard deviation is 6.8 meters. Generally we are interested not in the variation of the measurements themselves, but how uncertain we are of the average of the measurements. The uncertainty of this mean value is given, for a normal distribution, by the so-called "standard deviation of the mean", which can be found by dividing the standard deviation by the square root of the number of measurements,

$$\sigma_{\text{mean}} = \frac{\sigma}{\sqrt{N}}\,. \tag{A.2}$$

So, in this example, the uncertainty of the mean is 3.0 meters. We can thus report the length as $52 \pm 3$ m.

Note that if we take more measurements, the standard deviation of those measurements will not generally change, since the variability of our measurements shouldn't change over time. However, the standard deviation of the mean, and thus the uncertainty, will decrease.

## A.2 Propagation of uncertainty

When we use an uncertain quantity in a calculation, the result is also uncertain. To determine by how much, we give some simple rules for basic calculations, and then a more general rule for use with any calculation which requires knowledge of calculus. Note that these rules are strictly valid only for values that are normally distributed, though for the purpose of this course, we will use these formulas regardless of the underlying distributions, unless otherwise stated, for simplicity.

If the measurements are completely independent of each other, then for quantities $a \pm \delta a$ and $b \pm \delta b$, we can use the following formulas:

$$\text{For } c = a + b \text{ (or for subtraction), } \delta c = \sqrt{(\delta a)^2 + (\delta b)^2} \tag{A.3}$$

$$\text{For } c = ab \text{ (or for division), } \frac{\delta c}{c} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2} \tag{A.4}$$

$$\text{For } c = a^n,\ \frac{\delta c}{c} = n\frac{\delta a}{a} \tag{A.5}$$

For other calculations, there is a more general formula not discussed here.

| Expression | Implied uncertainty |
|---|---|
| 12 | 0.5 |
| 12.0 | 0.05 |
| 120 | 5 |
| 120. | 0.5 |

Table A.1: Expression of numbers and their implied uncertainty.

#### What if there is no reported uncertainty?

Sometimes you'll be calculating with numbers that have no uncertainty given. In some cases, the number is exact. For example, the circumference $C$ of a circle is given by $C = 2\pi r$. Here, the coefficient, $2\pi$, is an exact quantity and you can treat its uncertainty as zero. If you find a value that you think is uncertain, but the uncertainty is not given, a good rule of thumb is to assume that the uncertainty is half the right-most significant digit. So if you are given a measured length of 1400 m, then you might assume that the uncertainty is 50 m. This is an assumption, however, and should be described as such in your lab report. For more examples, see Table A.1.

#### How many digits to report?

After even a single calculation, a calculator will often give ten or more digits in an answer. For example, if I travel $11.3 \pm 0.1$ km in $350 \pm 10$ s, then my average speed will be the distance divided by the duration. Entering this into my calculator, I get the resulting value "`0.0322857142857143`". Perhaps it is obvious that my distance and duration measurements were not precise enough for all of those digits to be useful information. We can use the propagated uncertainty to decide how many decimals to include. Using the formulas above, I find that the uncertainty in the speed is given by my calculator as "`9.65683578099600e-04`", where the '`e`' stands for "times ten to the". I definitely do not know my uncertainty to 14 decimal places. For reporting uncertainties, it general suffices to use just the 1 or 2 left-most significant digits, unless you have a more sophisticated method of quantifying your uncertainties. So here, I would round this to 1 significant digit, resulting in an uncertainty of 0.001 km/s. Now I have a guide for how many digits to report in my value. Any decimal places to the right of the one given in the uncertainty are distinctly unhelpful, so I report my average speed as "$0.032 \pm 0.001$ km/s". You may also see the equivalent, more succinct notation "0.032(1) km/s".

## A.3 Comparing two values

If we compare two quantities and want to find out how different they are from each other, we can use a measure we call a $t'$ value (pronounced "tee prime"). This measure is not a standard statistical measure, but it is simple and its meaning is clear for us.

Operationally, for two quantities having the same unit, $a \pm \delta a$ and $b \pm \delta b$, the measure is defined as[2]

$$t' = \frac{|a-b|}{\sqrt{(\delta a)^2 + (\delta b)^2}} \tag{A.6}$$

If $t' \lesssim 1$, then the values are so close to each other that they are indistinguishable. It is either that they represent the same true value, or that the measurement should be improved to reduce the uncertainty.

If $1 \lesssim t' \lesssim 3$, then the result is inconclusive. One should improve the experiment to reduce the uncertainty.

If $t' \gtrsim 3$, then the true values are very probably different from each other.

[2] Statistically, if $\delta a$ and $\delta b$ are uncorrelated, random uncertainties, then $t'$ represents how many standard deviations the difference $a - b$ is away from zero.

APPENDIX B

# Rubrics

The scientific abilities rubrics are found on the following pages.

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **A11** | **Graph** | No graph is present. | A graph is present but the axes are not labeled. There is no scale on the axes. | The graph is present and axes are correctly labeled, but the axes do not correspond to the independent and dependent variables, or the scale is not accurate. | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. |

Table B.1: Rubric A: Ability to represent information in multiple ways

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **B1** | **Is able to identify the phenomenon to be investigated** | No phenomenon is mentioned | The description of the phenomenon to be investigated is confusing, or it is not the phenomenon of interest. | The description of the phenomenon is vague or incomplete. | The phenomenon to be investigated is clearly stated. |
| **B2** | **Is able to design a reliable experiment that investigates the phenomenon** | The experiment does not investigate the phenomenon. | The experiment may not yield any interesting patterns. | Some important aspects of the phenomenon will not be observable. | The experiment might yield interesting patterns relevant to the investigation of the phenomenon. |
| **B3** | **Is able to decide what physical quantities are to be measured and identify independent and dependent variables** | The physical quantities are irrelevant. | Only some of physical quantities are relevant. | The physical quantities are relevant. However, independent and dependent variables are not identified. | The physical quantities are relevant and independent and dependent variables are identified. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **B4** | **Is able to describe how to use available equipment to make measurements** | At least one of the chosen measurements cannot be made with the available equipment. | All chosen measurements can be made, but no details are given about how it is done. | All chosen measurements can be made, but the details of how it is done are vague or incomplete. | All chosen measurements can be made and all details of how it is done are clearly provided. |
| **B5** | **Is able to describe what is observed without trying to explain, both in words and by means of a picture of the experimental setup.** | No description is mentioned. | A description is incomplete. No labeled sketch is present. Or, observations are adjusted to fit expectations. | A description is complete, but mixed up with explanations or pattern. Or the sketch is present but is difficult to understand. | Clearly describes what happens in the experiments both verbally and with a sketch. Provides other representations when necessary (tables and graphs). |
| **B6** | **Is able to identify the shortcomings in an experiment and suggest improvements** | No attempt is made to identify any shortcomings of the experiment. | The shortcomings are described vaguely and no suggestions for improvement are made. | Not all aspects of the design are considered in terms of shortcomings or improvements. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. |
| **B7** | **Is able to identify a pattern in the data** | No attempt is made to search for a pattern. | The pattern described is irrelevant or inconsistent with the data. | The pattern has minor errors or omissions. Terms like “proportional” used without clarity, e.g. is the proportionality linear, quadratic, etc. | The pattern represents the relevant trend in the data. When possible, the trend is described in words. |
| **B8** | **Is able to represent a pattern mathematically (if applicable)** | No attempt is made to represent a pattern mathematically. | The mathematical expression does not represent the trend. | No analysis of how well the expression agrees with the data is included, or some features of the pattern are missing. | The expression represents the trend completely and an analysis of how well it agrees with the data is included. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **B9** | **Is able to devise an explanation for an observed pattern** | No attempt is made to explain the observed pattern. | An explanation is vague, not testable, or contradicts the pattern. | An explanation contradicts previous knowledge or the reasoning is flawed. | A reasonable explanation is made. It is testable and it explains the observed pattern. |

Table B.2: Rubric B: Ability to design and conduct an observational experiment [3].

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **C1** | **Is able to identify the hypothesis to be tested** | No mention is made of a hypothesis. | An attempt is made to identify the hypothesis to be tested but it is described in a confusing manner. | The hypothesis to be tested is described but there are minor omissions or vague details. | The hypothesis is clearly, specifically, and thoroughly stated. |
| **C2** | **Is able to design a reliable experiment that tests the hypothesis** | The experiment does not test the hypothesis. | The experiment tests the hypothesis, but due to the nature of the design it is likely the data will lead to an incorrect judgment. | The experiment tests the hypothesis, but due to the nature of the design there is a moderate chance the data will lead to an inconclusive judgment. | The experiment tests the hypothesis and has a high likelihood of producing data that will lead to a conclusive judgment. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **C4** | **Is able to make a reasonable prediction based on a hypothesis** | No prediction is made. The experiment is not treated as a testing experiment. | A prediction is made, but it is identical to the hypothesis, OR prediction is made based on a source unrelated to the hypothesis being tested, or is completely inconsistent with hypothesis being tested, OR prediction is unrelated to the context of the designed experiment. | Prediction follows from hypothesis but is flawed because relevant assumptions are not considered, OR prediction is incomplete or somewhat inconsistent with hypothesis, OR prediction is somewhat inconsistent with the experiment. | A prediction is made that follows from hypothesis, is distinct from the hypothesis, accurately describes the expected outcome of the experiment, and incorporates relevant assumptions if needed. |
| **C5** | **Is able to identify the assumptions made in making the prediction** | No attempt is made to identify assumptions. | An attempt is made to identify assumptions, but the assumptions are irrelevant or are confused with the hypothesis. | Relevant assumptions are identified but are not significant for making the prediction. | Sufficient assumptions are correctly identified, and are significant for the prediction that is made. |
| **C6** | **Is able to determine specifically the way in which assumptions might affect the prediction** | No attempt is made to determine the effects of assumptions. | The effects of assumptions are mentioned but are described vaguely. | The effects of assumptions are determined, but no attempt is made to validate them. | The effects of assumptions are determined and the assumptions are validated. |
| **C7** | **Is able to decide whether the prediction and the outcome agree/disagree** | No mention of whether the prediction and outcome agree/disagree. | A decision about the agreement/disagreement is made but is not consistent with the results of the experiment. | A reasonable decision about the agreement/disagreement is made but experimental uncertainty is not taken into account. | A reasonable decision about the agreement/disagreement is made and experimental uncertainty is taken into account. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **C8** | **Is able to make a reasonable judgment about the hypothesis** | No judgment is made about the hypothesis. | A judgment is made but is not consistent with the outcome of the experiment. | A judgment is made, is consistent with the outcome of the experiment, but assumptions are not taken into account. | A judgment is made, is consistent with the outcome of the experiment, and assumptions are taken into account. |

Table B.3: Rubric C: Ability to design and conduct a testing experiment [3].

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **D1** | **Is able to identify the problem to be solved** | No mention is made of the problem to be solved. | An attempt is made to identify the problem to be solved but it is described in a confusing manner. | The problem to be solved is described but there are minor omissions or vague details. | The problem to be solved is clearly stated. |
| **D2** | **Is able to design a reliable experiment that solves the problem.** | The experiment does not solve the problem. | The experiment attempts to solve the problem but due to the nature of the design the data will not lead to a reliable solution. | The experiment attempts to solve the problem but due to the nature of the design there is a moderate chance the data will not lead to a reliable solution. | The experiment solves the problem and has a high likelihood of producing data that will lead to a reliable solution. |
| **D3** | **Is able to use available equipment to make measurements** | At least one of the chosen measurements cannot be made with the available equipment. | All of the chosen measurements can be made, but no details are given about how it is done. | All of the chosen measurements can be made, but the details about how they are done are vague or incomplete. | All of the chosen measurements can be made and all details about how they are done are provided and clear. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **D4** | **Is able to make a judgment about the results of the experiment** | No discussion is presented about the results of the experiment. | A judgment is made about the results, but it is not reasonable or coherent. | An acceptable judgment is made about the result, but the reasoning is incomplete, OR uncertainties are not taken into account, OR assumptions are not discussed, OR the result is written as a single number. | An acceptable judgment is made about the result, with clear reasoning. The effects of assumptions and experimental uncertainties are considered. The result is written as an interval. |
| **D5** | **Is able to evaluate the results by means of an independent method** | No attempt is made to evaluate the consistency of the result using an independent method. | A second independent method is used to evaluate the results. However there is little or no discussion about the differences in the results due to the two methods. | A second independent method is used to evaluate the results. The results of the two methods are compared correctly using experimental uncertainties. But there is little or no discussion of the possible reasons for the differences when the results are different. | A second independent method is used to evaluate the results and the evaluation is correctly done with the experimental uncertainties. The discrepancy between the results of the two methods, and possible reasons are discussed. |
| **D7** | **Is able to choose a productive mathematical procedure for solving the experimental problem** | Mathematical procedure is either missing, or the equations written down are irrelevant to the design. | A mathematical procedure is described, but is incorrect or incomplete, due to which the final answer cannot be calculated. Or units are inconsistent. | Correct and complete mathematical procedure is described but an error is made in the calculations. All units are consistent. | Mathematical procedure is fully consistent with the design. All quantities are calculated correctly with proper units. Final answer is meaningful. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **D8** | **Is able to identify the assumptions made in using the mathematical procedure** | No attempt is made to identify any assumptions. | An attempt is made to identify assumptions, but the assumptions are irrelevent or incorrect for the situation. | Relevant assumptions are identified but are not significant for solving the problem. | All relevant assumptions are correctly identified. |
| **D9** | **Is able to determine specifically the way in which assumptions might affect the results** | No attempt is made to determine the effects of assumptions. | The effects of assumptions are mentioned but are described vaguely. | The effects of assumptions are determined, but no attempt is made to validate them. | The effects of assumptions are determined and the assumptions are validated. |

Table B.4: Rubric D: Ability to design and conduct an application experiment [3].

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **F1** | **Is able to communicate the details of an experimental procedure clearly and completely** | Diagrams are missing and/or experimental procedure is missing or extremely vague. | Diagrams are present but unclear and/or experimental procedure is present but important details are missing. It takes a lot of effort to comprehend. | Diagrams and/or experimental procedure are present and clearly labeled but with minor omissions or vague details. The procedure takes some effort to comprehend. | Diagrams and/or experimental procedure are clear and complete. It takes no effort to comprehend. |
| **F2** | **Is able to communicate the point of the experiment clearly and completely** | No discussion of the point of the experiment is present. | The experiment and findings are discussed but vaguely. There is no reflection on the quality and importance of the findings. | The experiment and findings are communicated but the reflection on their importance and quality is not present. | The experiment and findings are discussed clearly. There is deep reflection on the quality and importance of the findings. |

Table B.5: Rubric F: Ability to communicate scientific ideas [3].

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **G1** | **Is able to identify sources of experimental uncertainty** | No attempt is made to identify experimental uncertainties. | An attempt is made to identify experimental uncertainties, but most are missing, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and instrumental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between instrumental and random uncertainty. |
| **G2** | **Is able to evaluate specifically how identified experimental uncertainties affect the data** | No attempt is made to evaluate experimental uncertainties. | An attempt is made to evaluate uncertainties, but most are missing, described vaguely, or incorrect. Or the final result does not take uncertainty into account. | The final result does take the identified uncertainties into account but is not correctly evaluated. Uncertainty propagation is not used or is used incorrectly. | The experimental uncertainty of the final result is correctly evaluated. Uncertainty propagation is used appropriately. |
| **G3** | **Is able to describe how to minimize experimental uncertainty and actually do it** | No attempt is made to describe how to minimize experimental uncertainty and no attempt to minimize is present. | A description of how to minimize experimental uncertainty is present, but there is no attempt to actually minimize it. | An attempt is made to minimize the uncertainty in the final result is made but the method is not very effective. | The uncertainty is minimized in an effective way. |
| **G4** | **Is able to record and represent data in a meaningful way** | Data are either absent or incomprehensible. | Some important data are absent or incomprehensible. They are not organized in tables or the tables are not labeled properly. | All important data are present, but recorded in a way that requires some effort to comprehend. The tables are labeled but labels are confusing. | All important data are present, organized, and recorded clearly. The tables are labeled and placed in a logical order. |

| | Scientific Ability | Missing | Inadequate | Needs Improvement | Adequate |
|---|---|---|---|---|---|
| **G5** | **Is able to analyze data appropriately** | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed or inappropriate. | The analysis is appropriate but it contains errors or omissions. | The analysis is appropriate, complete, and correct. |

Table B.6: Rubric G: Ability to collect and analyze experimental data [3].

APPENDIX C

# Lab Report Format

## C.1 General

- The report should be typed for ease of reading. Text should be double-spaced, and the page margins (including headers and footers) should be approximately 2.5 cm, for ease of marking by the grader. Each page should be numbered.
- The first page should include the title of the lab; lab section day, time, and number; and the names of the members of your lab team.

## C.2 Organizing the report

The report should follow the sequence of the report checklist. Answers to questions and inclusion of tables and figures should appear in the order they are referenced in the manual. In general, include the following:

- For any calculations that you perform using your data, and the final results of your calculation, you must show your work in order to demonstrate to the grader that you have actually done it. Even if you're just plugging numbers into an equation, you should write down the equation and all the values that go into it. This includes calculating uncertainty and propagation of uncertainty.
- If you are using software to perform a calculation, you should explicitly record what you've done. For example, "Using Excel we fit a straight line to the velocity vs. time graph. The resulting equation is $v = (0.92\,\mathrm{m/s^2})t + 0.2\,\mathrm{m/s}$."
- Answers to any questions that appear in the lab handout. Each answer requires providing justification for your answer.

## C.3 Graphs, Tables, and Figures

Any graph, table, or figure (a figure is any graphic, for example a sketch) should include a caption describing what it is about and what features are important, or any helpful orientation to it. The reader should be able to understand the basics of what a graph, table, or figure is saying and why it is important without referring to the text. For more examples, see any such element in this lab manual.

Each of these elements has some particular conventions.

## Tables

A table is a way to represent tabular data in a quantitative, precise form. Each column in the table should have a heading that describes the quantity name and the unit abbreviation in parentheses. For example, if you are reporting distance in parsecs, then the column heading should be something like "distance (pc)". This way, when reporting the distance itself in the column, you do not need to list the unit with every number.

## Graphs

A graph is a visual way of representing data. It is helpful for communicating a visual summary of the data and any patterns that are found.

The following are necessary elements of a graph of two-dimensional data (for example, distance vs. time, or current vs. voltage) presented in a scatter plot.

- **Proper axes.** The conventional way of reading a graph is to see how the variable on the vertical axis changes when the variable on the horizontal axis changes. If there are independent and dependent variables, then the independent variable should be along the horizontal axis.
- **Axis labels.** The axes should each be labeled with the quantity name and the unit abbreviation in parentheses. For example, if you are plotting distance in parsecs, then the axis label should be something like "distance (pc)".
- **Uncertainty bars.** If any quantities have an uncertainty, then these should be represented with so-called "error bars", along both axes if present. If the uncertainties are smaller than the symbol used for the data points, then this should be explained in the caption.

# Bibliography

[1] E. Etkina, G. Planinsic, and A. Van Heuvelen, *College physics: explore and apply*, 2nd (Pearson, New York, 2014), 981 pp.

[2] E. Etkina, “Millikan award lecture: students of physics—listeners, observers, or collaborative participants in physics scientific practices?”, American Journal of Physics **83**, 669 (2015).

[3] E. Etkina, A. Van Heuvelen, S. White-Brahmia, D. T. Brookes, M. Gentile, S. Murthy, D. Rosengrant, and A. Warren, “Scientific abilities and their assessment”, Physical Review Special Topics - Physics Education Research **2** (2006) `10.1103/PhysRevSTPER.2.020103`.