Laboratory Manual

PHSC 12600 Matter, Energy, Space, & Time

The University of Chicago

Autumn 2021

Labs

LAB 1

How fast is light?[1]

1.1 Introduction

[add Greek and Arab theorists]

In the early 1600s, the Italian physicist Galileo Galilei was the first to attempt to measure the speed of light with an ingenious experiment. On top of a hill in the beautiful Tuscan country (Fig. ???), Galileo opened the shutter of his lantern and started a clock (he used his pulse as a timer!). At the sight of Galileo's light, an assistant on a nearby hill opened the shutter of his own lantern. Galileo then stopped the "clock" as soon as he saw the light from the assistant's lantern. He would measure the speed of light as the ratio of twice the distance between the hilltops (the total distance traveled by the light) to the time measured with his "clock". Galileo repeated the experiment from various hill tops, and, no matter how far apart they were, he obtained the same time interval, concluding that his method was not accurate enough to measure the speed of light. Indeed, the light time travel was much smaller than the minimum time interval of the "clock" (~ 1 s since the pulse rate is ~ 60 per minute) and the time measured by Galileo was essentially determined by human reaction time.

After Galileo's first attempt, many ingenious experiments have determined the speed of light with amazing precision (4 parts per billion), including those employing a fast rotating mirror by Albert Michelson, professor at University of Chicago and Nobel Prize in Physics (1907).

[1] Developed by Paolo Privatera 2017, revised by Brent Barker 2021

Figure 1.1: Tuscany Hills

In this lab, you will measure the speed of light with a method similar to Galileo's but with some helpful improvements: a mirror will replace Galileo's assistant (eliminating the delay introduced by his reaction time!) and the time of travel will be measured with nanosecond resolution by an extremely fast light detector.

1.2 Forming Groups

Find your group of 2–3 people. You can change groups from week to week, if you'd like.

1. Once you have a group, meet with each other and decide a) what tools you will use to communicate and collaborate, b) when you will meet, c) what you will do when you need to change an agreement, and d) what you will do when a member has a concern about how the group is functioning. **Record your agreements.**

Team roles

2. **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 rotate each lab, and you will report at the end of the lab report on how it went for each role. Some members will be holding more than one role. For example, you could have 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 think of them more like functions that every team needs to carry out, and then reflect on how the team executed each function.

Add members to Canvas lab report assignment group

3. On Canvas, navigate to the People section, then to the "Lab 1 Groups" tab. Find a group that is not yet used, and have each person in your group add themselves to that same lab group.

This enables group grading of your lab report. Only one person will submit the group report, and all members of the group will receive the grade and have access to view the graded assignment.

1.3 The Scientific Cycle[2]

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 (the hypothetico-deductive cycle), summarized in Figure 1.2.

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,

[2] adapted from Etkina, Planinsic, Van Heuvelen, College Physics, 2nd ed. (2014)

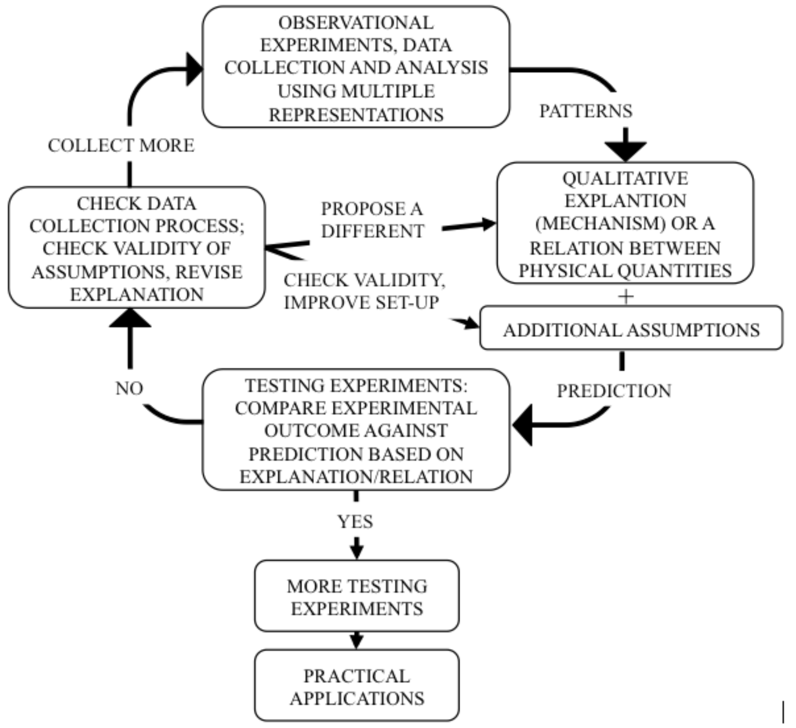

Figure 1.2: A model of the process some scientists go through to create knowledge.

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.”

1.4 Application experiment: measure the speed of light

Goal

Use the kinematic equations to experimentally determine the speed of light produced by a pulsed laser.

Available equipment

- Oscilloscope
- Pulsed laser
- Photodiode

Warning: Laser Hazard! The power of our lasers is low enough that the normal human blink reflex is sufficient to protect against incidental eye exposure.

That being said, the following rules reduce the risk of eye exposure to laser light:

1. Do not direct the laser beam into anyone's eye.
2. Be aware of the laser reflecting off of mirror-like surfaces and where that beam goes.
3. Turn off the laser when not in use.
4. Keep the laser pointing horizontally and near the plane of the table, while keep your eyes above that plane.
5. To determine whether the laser is on, put your hand or a light-colored object in front of the beam, rather than looking into the laser aperture.

Self-assessment: To help you improve your scientific abilities, we provide you with self-assessment rubrics. A rubric is a scoring system. 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.

Rubrics to focus on during this experiment:

See Appendix B for more details.

- **A11:** Graph
- **D4:** Is able to make a judgment about the results of the experiment
- **G1:** Is able to identify sources of experimental uncertainty
- **G2:** Is able to evaluate specifically how identified experimental uncertainties affect the data
- **G4:** Is able to record and represent data in a meaningful way
- **F1:** Is able to communicate the details of an experimental procedure clearly and completely
- **F2:** Is able to communicate the point of the experiment clearly and completely

Speed of light apparatus

You will use a *time-of-flight* method to measure the speed of light, as illustrated in Figs. 1.3–1.4. A red laser diode emits periodic flashes of light of very short duration (few 10^{-9} s). Each pulse of light is directed toward a distant mirror, placed at a distance L from the laser, where it is reflected back toward a light detector (photodiode) located on top of the laser housing. The speed of the light pulse is given by the distance of travel ($D \approx 2L$) divided by the time t required by the pulse to travel to the distant mirror and back:

$$v = c = \frac{2L}{t} \tag{1.1}$$

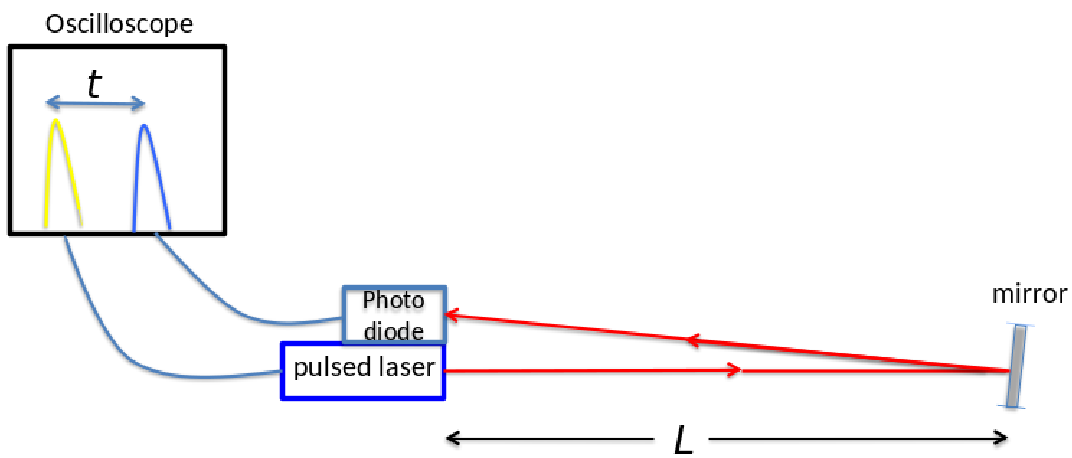

Figure 1.3: Sketch of the speed of light apparatus.

You will measure the distance L with a measuring tape or meter stick, while the time t is measured with the help of an oscilloscope. The electronic circuit driving the laser generates a voltage pulse coincident in time with the firing of the laser flash (yellow line, CH1). A second voltage pulse (blue line, CH2) is produced by the photodiode when hit by the returning light flash. The time difference between these two voltage pulses gives the time of travel t.

Aligning the mirror

The alignment of the laser-mirror-photodiode requires a bit of practice but it is not too hard (and is fun!). You will use a sheet of white paper to "catch" the laser spot when doing the alignment.

4. Place the mirror the desired distance from the laser. This is your distance L. A useful first distance is 1 meter.

5. Place the white paper at the distance L and see where the laser spot is located. Position the mirror so that the laser spot is approximately at its center (you may have to move the laser base or the mirror vertically.)

6. To catch the reflected laser, slowly move the white paper from the sides (left, right and top with respect to the laser axis) to intercept the laser. Perform this operation with the white paper placed approximately half way between the laser and the mirror. You should find two spots, one of which (the reflected laser beam: "reflected spot") will disappear when you catch the other (the beam coming directly from the laser: "direct spot").

Figure 1.4: The speed of light setup.

7. Once you have identified the reflected spot, move the alignment knobs behind the mirror (slowly, they are very sensitive!) to place it close the direct spot (catching the spots with the white paper will help you during this procedure). If the reflected spot is too much on the side, you can also rotate the base of the mirror to bring it back along the laser beam axis, and then do the fine adjustments with the mirror alignment knobs.

8. Follow with the white paper the reflected spot back to the laser/photodiode housing. Note that the reflected spot will be quite diffused, particularly for large L.

9. By rotating the base of the mirror and/or with small adjustments of the mirror alignment knobs, move the reflected spot so that the photodiode is approximately at its center. Look at the signal pulse from the photodiode (blue line) and do small adjustment to maximize it so that it is approximately symmetric with a peak height $\geqslant 15\,\mathrm{mV}$.

Observing the signal

The function of the oscilloscope is to detect a small repeating signal ("oscillation") and display it in a way useful for analysis. It works at the high frequencies we need (billions of cycles per second, or gigahertz).

10. Be sure that the oscilloscope is setup to display individual pulses (Press "Acquire", then "Sample", Figs. 1.5 and 1.6).

11. Note the frequency of the periodic flashes as displayed in the lower right corner of the screen. It should be about 100 kHz, since that's the frequency the laser is pulsing at.

12. Expand the time scale by turning the Horizontal Scale knob (see Fig. 1.5, right) and observe that each of these periodic pulses is actually two, closely spaced pulses (Fig. 1.5, left).

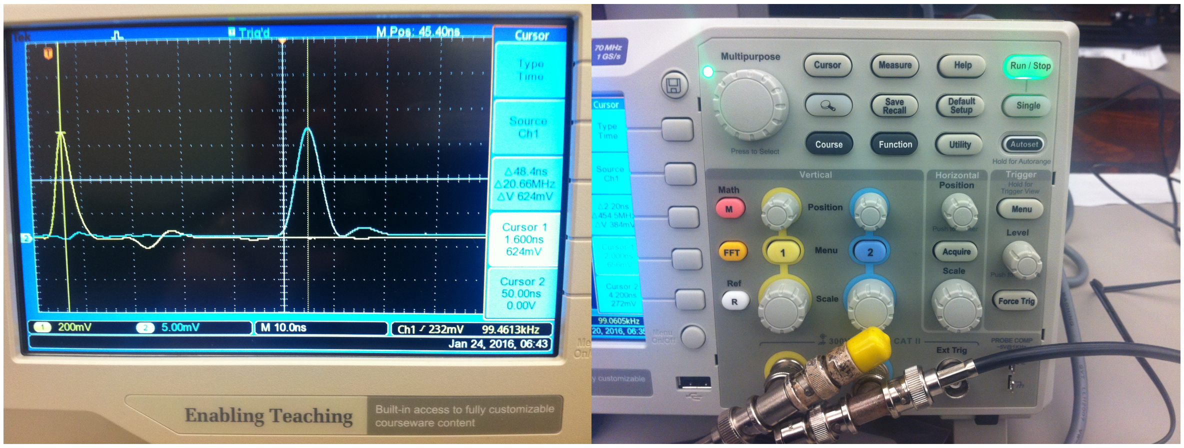

Figure 1.5: Left: Oscilloscope screen with Cursor time measurement. Right: Oscilloscope commands.

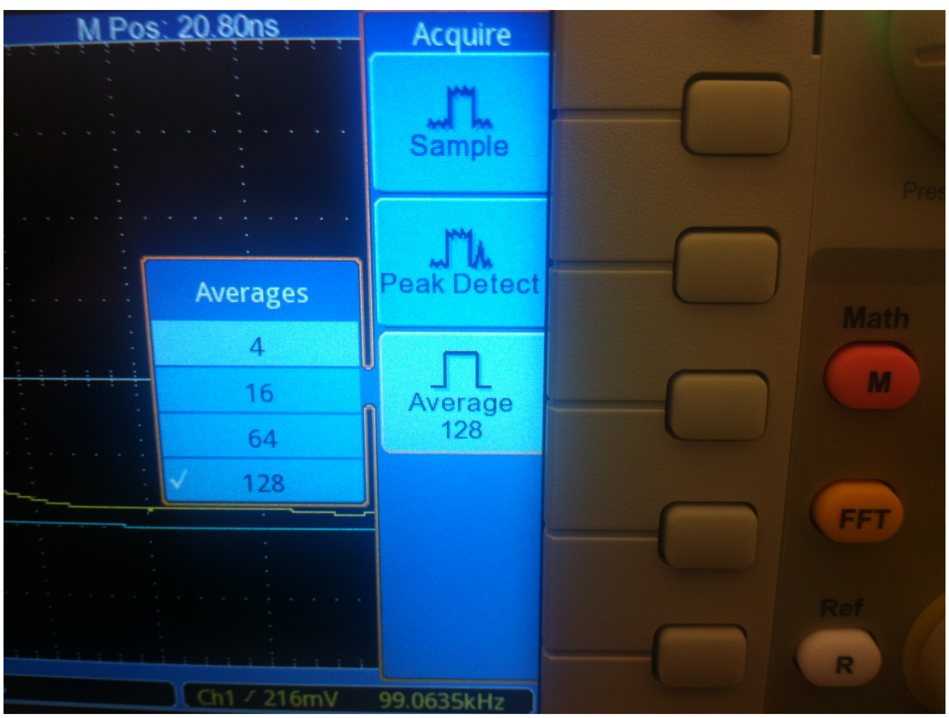

Figure 1.6: Performing Averages with the oscilloscope

The first pulse (yellow line) corresponds to the time when the laser emits the flash, the second pulse (blue line) corresponds to the time of arrival of the light flash at the photodiode.

Doing one measurement

Here you'll actually do a measurement of the speed of light by measuring the distance and time duration and applying Equation 1.1.

Measuring distance

13. With the laser aligned and both pulses visible, measure the mirror distance L.

A measurement of a physical quantity is not useful without an estimate of the uncertainty of the measurement.

14. Skim the introduction and Section A.1 of Appendix A.
15. Identify some possible sources of uncertainty for the mirror distance measurement. **Record your answers.**
16. For each source of uncertainty, decide on the type of uncertainty — instrumental or random. **Record your answers.**
17. For each source of uncertainty, estimate the amount of uncertainty. **Record your answers.**
18. For this measurement, pick the greatest uncertainty from the various sources and ignore the others. Treat this as the uncertainty of this measurement. **Record your final determination of L and uncertainty δL.** Express this as $L \pm \delta L$, for example $L = 1.02 \pm 0.01$ meters.

Measuring time

19. To optimally measure the difference in time between the two pulses, maximize the resolution of the time (Horizontal) scale while keeping both pulses in the screen. The resolution is displayed in the lower middle of the screen, labeled "M". Typically you will choose a 5 ns/division or 10 ns/division in the horizontal scale. Place the source laser pulse (CH1, yellow line) as far left as possible using the Horizontal Position knob so that the full horizontal scale can be used for the measurements.
20. Optimize the photodiode pulse (CH2, blue line) by aligning the laser spot on the photodiode. The resulting pulse should be approximately symmetric with a peak height $\geqslant 15$ mV. *Note: always keep the vertical scale of Channel 2 at $\geqslant 5$ mV/division, as shown in the lower left marked "2".*

Next you will set up the oscilloscope to perform the average of 128 pulses, which will provide improved accuracy in the determination of the position of the pulses.

21. To set the oscilloscope for the average measurement (Fig. 1.6), press "Acquire", then press "Average" and rotate the Multipurpose knob till the number 128 (i.e. average of 128 pulses) is highlighted, and press the Multipurpose knob to select. Press "Menu off" to eliminate the Menu from the screen.

Next you will use the time cursors to measure the time difference t between the peaks of the two pulses.

22. Press "Cursor" (Fig. 1.5, right). Check that cursor "Type" is "Time", then press "Cursor 1" in the Cursor Menu and move the cursor by turning the Multipurpose knob so that it coincides with the peak of the source pulse. Press "Cursor 2" and move the cursor until it coincides with the peak of the detector pulse. The time difference between the two cursors (corresponding to the time of travel t) will be displayed as "Δ .. ns" in the Cursor Menu (third tab from the top). **Record your measured time difference.**

23. Identify the sources of uncertainty, estimate each of them, choose the largest, and **record your time difference t and its uncertainty δt.**

24. Use Equation 1.1 to find your measurement of the speed of light v_c.

25. To find the uncertainty in your measured v_c, we must propagate the uncertainty from L and t. Since the formula involves division of these two variables, use Equation A.4 to find δv_c. **Record your calculation of $v_c \pm \delta v_c$**

It is okay if this measurement is much different from the standard value of $c \approx 3 \times 10^8$ m/s. We will examine a possible reason for this in the next section. It should be within a factor of 2 or so at this point. If not, check with your instructor.

26. Press "Acquire", then "Sample". This will return the oscilloscope to display individual pulses.

1.5 Checking assumptions

In our model of the scientific cycle, sources of uncertainty are ones that are quantifiable — we can estimate the effect and include it as an interval within which we are confident. We use *assumption* to mean things that we are assuming are true that, if not true, would change our result in ways that we cannot or are not estimating. Some assumptions are more about troubleshooting — for example, we assume that the oscilloscope is working as expected. Others are about our measurement technique. For example, there is a vertical distance between the laser source and the detector. This means that the path the light travels is not simply $2L$.

27. By assuming the path the light travels is $2L$, will you over- or under-estimate value of c, compared with using a more accurate length? **Record your answer.**

28. Estimate how much your measurement of the speed of light will change if you use the correct value for the return path (note: the distance between the laser and the photodiode is 4 cm). For simplicity, make your estimate only for the measurement where the mirror was at the maximum distance. Do you think this is a small or large effect? **Record your answers.**

Another assumption is that the lag time from detector to oscilloscope and from source to oscilloscope is the same. That is, the time difference recorded in the oscilloscope includes the time for the signals from the laser and detector to reach it. Since we are talking about time differences on the order of nanoseconds, small differences in cable length, for example, could change things.

This fixed difference in length d_e is the same no matter the mirror distance $D = 2L$. In fact, it should be the same error in length every time. So the recorded time difference t would actually be

$$\text{total distance} = vt \tag{1.2}$$
$$2L + d_e = vt \tag{1.3}$$
$$2L = vt - d_e \tag{1.4}$$

Notice that the last equation is in the same form as that of a straight line, $y = mx + b$. So if we take a series of measurements of t for different distances $2L$, and plot $2L$ vs. t, then the slope of the graph will be the speed of light v, and that effective length difference d_e will be the y-intercept.

length (m)	distance = $2L$ (m)	time (10^{-9} s)
...	...	...

Table 1.1: Sample data collection table.

29. Measure the time difference for at least 5 different mirror distances, **recording your measurement in a table**, including the distance L between the laser and the mirror that you have measured with the measuring tape or meter stick. See Table 1.1 for a sample table format.

30. Once your measurements are completed, graph the data of your table in a plot with time of travel t in the horizontal axis and distance of travel ($D = 2L$) in the vertical axis.

31. To determine the speed of light c, fit your data with a line (e.g. with Excel by displaying your data with Scatter, and then using Trendline; select 'Display Equation on Chart' in Trendline Options). The slope of the line will be your estimate of the speed of light. (NOTE: pay attention to the units). **Take a screenshot of your graph for your report.**

In this case, to determine the uncertainty, you will not use the uncertainty of each individual point. Instead, you will use the coefficient of determination, r^2, which is given by your plotting program, along with the number of data points you took, N, to find the uncertainty, which is the standard error SE of the slope m, given as

$$SE(m) = m\sqrt{\frac{1 - r^2}{r^2(N-2)}} \tag{1.5}$$

32. Find the uncertainty in the speed of light measurement using Equation 1.5. **Record your new determination of c, with its uncertainty.**

33. Compare your result with the known value of the speed of light, 299 792 458 m/s. To compare, use the t' statistic as described in Appendix A.3.

1.6 Revisiting Galileo's technique

34. Measure your reaction time with a stopwatch (highly likely you have one in your cell phone, or ask the instructor if you need one). Start-stop the stopwatch and record the time. Take 10 measurements and calculate their average as an estimate of your reaction time.**Record your results.**

35. Now, imagine you climb on top of a hill in beautiful Tuscany and shoot a laser pulse (by pressing a button at the same time of the start in the stopwatch) towards a mirror placed 2 km away. You press the stop in the stopwatch as soon as you see the returning laser pulse. Would you be able to measure the speed of light? (Calculate the time of travel of the laser pulse and compare it with your reaction time). **Record your answer and calculation.**

36. At what distance should the mirror be placed for you to be able to measure the speed of light (say with a 20% uncertainty) using the stopwatch? **Record your answer.**

1.7 Group dynamics

37. Write a 100–200 word 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? What successes and challenges in group functioning did you have? What do you want to do differently next time?

1.8 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, as well as F1 and F2, applied to the entire report), 3 points for attendance and participation, and 6 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

Local Gravitational Field

One of Newton's revelations was that physical laws that governed the movement of objects near Earth also predicted the movements of objects in the sky. The apocryphal story of an apple falling on Newton's head brings to mind the mechanism of gravity — the phenomenon of massive objects attracting each other. In this lab, you will measure the strength that gravity has where we are, near the Earth's surface. This measurement might also enable us to learn more about the mass of the Earth itself in a future lab.

2.1 Learning goals

- Understand Newton's law of universal gravitation and its linear approximation
- Identify sources of statistical and systematic error
- Demonstrate an ability to make careful measurements
- Demonstrate proficiency in basic calculations and plotting
- Explain the importance of repeated measurements and sufficiently large datasets

Team roles

1. **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 rotate each lab, and you will report at the end of the lab report on how it went for each role. Some members will be holding more than one role. For example, you could have 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 think of them more like functions that every team needs to carry out, and then reflect on how the team executed each function.

Add members to Canvas lab report assignment group

2. On Canvas, navigate to the People section, then to the "L2 G Field [number]" tab. Find a group that is not yet used, and have each person in your group add themselves to that same lab group.

This enables group grading of your lab report. Only one person will submit the group report, and all members of the group will receive the grade and have access to view the graded assignment.

2.2 Scientific Background

The gravitational field strength and Newton's second law

The force of gravity, F, between two objects with mass m_1 and m_2 and whose centers are separated by a distance R is given by Newton's law,

$$F_{\text{gravity}} = G\frac{m_1\, m_2}{r^2}\,, \tag{2.1}$$

where the Newtonian constant of gravitation $G = 6.67408(31) \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$. Astronomers apply Newton's law to infer fundamental information about astrophysical objects, for example the mass of binary stars. Indeed, this is one of the most common methods by which astronomers "weigh" astrophysical objects, including the Earth itself. For measuring the force acting on an object of mass m that is affected predominantly by the Earth's gravity, the force acting on it would be

$$F_{\text{Earth}} = \frac{GM_\oplus}{(R_\oplus + h)^2}m \tag{2.2}$$

where $M_\oplus$ and $R_\oplus$ are the mass and radius of the Earth, respectively, and h is the height above the Earth.

For objects near the Earth's surface, where h is much less than $R_\oplus$, h can be treated as zero, resulting in a constant gravitational force, with Equation 2.2 reducing to

$$F_{\text{Earth}} = \frac{GM_\oplus}{(R_\oplus)^2}m\,. \tag{2.3}$$

Notice that on the right-hand-side of this equation, the only variable is the mass. The others, together, constitute the *strength of the local gravitational field*, g (sometimes pronounced "little g"). So our simplified equation is

$$F_{\text{Earth}} = gm\,, \tag{2.4}$$

where we have made the substitution

$$g = \frac{GM_\oplus}{(R_\oplus)^2}\,. \tag{2.5}$$

Notice that we have taken a complicated inverse square equation (Equation 2.2) and converted it to a much simpler one (Equation 2.4). This process is called *linearization* and is a trick astronomers often use to make calculations more manageable. You will encounter this technique throughout this and other PHSC courses.

We see from Equation 2.5 that if we can make accurate measurements of g, G, and $R_\oplus$, we can calculate the mass of the Earth. We'll look up $R_\oplus$ online, and next week we will measure G. To find g, we note that Newton's second law of motion states that the acceleration a of an object is directly proportional to the net force F_{net} acting on it and inversely proportional to its mass, m, or, more succinctly and slightly rearranged,

$$F_{\text{net}} = ma\,. \tag{2.6}$$

If the Earth's gravity is the only force acting on our object, then $F_{\text{net}} = F_{\text{Earth}}$, and substituting Equation 2.4, we find that

$$gm = ma\,, \tag{2.7}$$

and thus, simplifying,

$$a = g\,. \tag{2.8}$$

So, the acceleration of an object that is subject only to the Earth's gravity is equal to the local gravitational field strength. If we can measure the acceleration, then we can find g, and get one step closer to determining the mass of the Earth.

Constantly accelerated motion

If an object is subject to a constant force, then according to Newton's second law, it undergoes constant acceleration. If an object undergoes constant acceleration a, and we know the object's initial position x_0 and velocity v_0, then after a time duration t, we can derive using calculus that the object's position x and velocity v are given by

$$x = x_0 + v_0 t + \frac{1}{2}at^2 \tag{2.9}$$

and

$$v = v_0 + at\,. \tag{2.10}$$

2.3 Application experiment: determine $\boldsymbol{g}$ on the Earth's surface

Goal

Determine g near the Earth's surface by finding the acceleration of an object undergoing freefall (no substantial forces other than gravity) using two different methods.

Rubrics to focus on

See Appendix B for more details.

- **D4:** Is able to make a judgment about the results of the experiment
- **D5:** Is able to evaluate the results by means of an independent method
- **G1:** Is able to identify sources of experimental uncertainty
- **G2:** Is able to evaluate specifically how identified experimental uncertainties affect the data
- **G4:** Is able to record and represent data in a meaningful way
- **F1:** Is able to communicate the details of an experimental procedure clearly and completely
- **F2:** Is able to communicate the point of the experiment clearly and completely

Available equipment

- Stopwatch
- Dense object to drop
- Meter stick
- Camera (including the one on your phone)
- Computer with Tracker[1] installed.

[1] Open Source Physics Tracker can be downloaded from `https://physlets.org/tracker` and is also installed on the lab computers.

Method 1: freefall time

3. Drop the object from a known height and measure the time to fall with a stopwatch. Do this as many times as makes sense to you.
4. List the sources of uncertainty and determine whether each is a random uncertainty or an instrumental uncertainty.
5. Calculate the average fall time.
6. Calculate the standard deviation of the average fall time (using Equation A.2), and report the latter as the uncertainty in the average fall time.
7. Use the average fall time and the initial position and velocity of the object to calculate the acceleration.
8. Propagate the uncertainty in the time and position to find the uncertainty of your measured acceleration (see Section A.2)
9. Report the acceleration found by this method as "value ± uncertainty [units]". For example, $9.73 \pm 0.04\,\mathrm{m/s^2}$.

Method 2: Video tracking

It is helpful to use two methods to find the same quantity, so that mistakes or incorrect assumptions made in one method do not carry over to the other, and are thus more likely to be detected. In this method, you will record a video of an object falling, make a position vs. time plot, and fit the constant acceleration equation (Equation 2.9). You will use a computer program to make this analysis easier.

Record the video

10. Find a good object to drop. It should be dense enough to not be slowed down significantly by air resistance.
11. 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.
12. 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 positions, find out what parameters best fit the curve that is produced, and use those to find the acceleration.

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

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

15. In Tracker, open your video.

16. **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.

17. **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.

18. 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.

19. **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.

20. **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.

21. **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.

22. **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

23. **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)".

24. In the drop-down menu, select `View` → `Data Tool (Analyze...)`.

25. In the window that appears, above the plot, click `Analyze` → `Curve Fits`.

26. Notice that Eq. 2.9, which describes freefall, is a quadratic equation, which means the shape is a parabola. For "Fit Name", choose "Parabola" from the drop-down menu.

27. Use the Fit Equation and Parameter Values, comparing with Equation 2.9, to find the acceleration a, and thus the gravitational field strength g.

28. To get an uncertainty for this value, use the "rms dev" value, which describes the average deviation of the fit equation from the points, divide that by the average (mean) position, and multiply that by your value for the acceleration. You can find the mean position by selecting `Analyze` → `Statistics` and reading above the data table column.

Comparing the methods, final determination of g

29. Compare the values of g from the two methods using the t' statistic as described in Appendix A.3.
30. Use that comparison and your assessment of which method had fewer questionable assumptions to decide on your final answer for g (including an uncertainty). How close is it to the average g described, for example, on Wikipedia?

2.4 Group dynamics

31. Write a 100–200 word 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? What successes and challenges in group functioning did you have? What do you want to do differently next time?

2.5 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, as well as F1 and F2, applied to the entire report), 3 points for attendance and participation, and 6 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

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.

3.1 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.

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 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.

Add members to Canvas lab report assignment group

1. On Canvas, navigate to the People section, then to the "L3 Light Wave [number]" tab. Find a group that is not yet used, and have each person in your group add themselves to that same lab group.

This enables group grading of your lab report. Only one person will submit the group report, and all members of the group will receive the grade and have access to view the graded assignment.

3.3 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

- 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 available here: 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?

2. 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?
3. In the ripple tank, follow your TA's instructions to set 1 or 2 plungers and watch the wave crests (light color) expand away from the source, a plunger pushing down and up in the water.
4. Dip a spare plunger into the water to create a ripple (a single wave crest), or in the simulation, click anywhere in the tank. **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?
5. For the case of two plungers bobbing up and down, **observe and record** what happens to the wave crests as they overlap. What patterns do they create?
6. Summarize the difference between particles and waves in this case.

How do they deliver energy?

7. 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.
8. 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".
9. Press "Restart" to reset the string to neutral.
10. 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?
11. 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?
12. Summarize the difference between particles and waves in this case.

3.4 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

See Appendix B for more details.

- **C2:** Is able to design a reliable experiment that tests the hypothesis
- **C4:** Is able to make a reasonable prediction based on a hypothesis
- **C7:** Is able to decide whether the prediction and the outcome agree/disagree
- **C8:** Is able to make a reasonable judgment about the hypothesis
- **G4:** Is able to record and represent data in a meaningful way
- **F1:** Is able to communicate the details of an experimental procedure clearly and completely
- **F2:** Is able to communicate the point of the experiment clearly and completely

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)

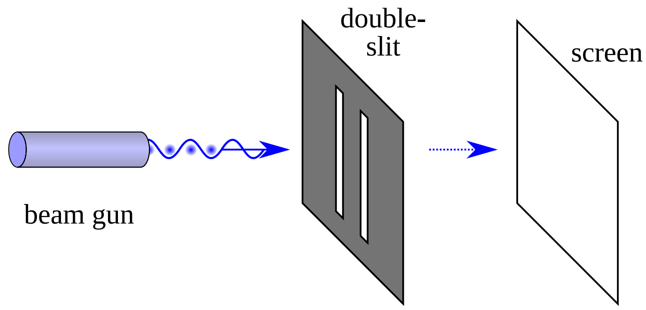

Figure 3.1: Experimental setup. Note that the light emitted from the beam gun (or laser) is broad enough to go through both slits.

Steps

13. Before turning on the lamp, examine each part of the device and ensure you know how it works.
14. 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.**
15. Develop an experimental procedure that will allow you to collect the data you need to compare to the predictions. **Record this procedure.**
16. Collect and record your relevant data.
17. 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 3.1 and presented to you with the laser, slit wheel, and screen in the lab.

Warning: Laser Hazard! The power of our lasers is low enough that the normal human blink reflex is sufficient to protect against incidental eye exposure.

That being said, the following rules reduce the risk of eye exposure to laser light:

1. Do not direct the laser beam into anyone's eye.
2. Be aware of the laser reflecting off of mirror-like surfaces and where that beam goes.
3. Turn off the laser when not in use.
4. Keep the laser pointing horizontally and near the plane of the table, while keep your eyes above that plane.
5. To determine whether the laser is on, put your hand or a light-colored object in front of the beam, rather than looking into the laser aperture.

18. Determine what each hypothesis (A) and (B) predicts the screen will look like. Where are the dark and bright regions?
19. Ask your TA for the experimental result that was done using a red laser.

20. Compare the experimental outcome to the predictions and determine which, if any, of the predictions agree with the outcome, and to what degree.

Conclusion

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

3.5 Group dynamics

22. Write a 100–200 word 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? What successes and challenges in group functioning did you have? What do you want to do differently next time?

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, as well as F1 and F2, applied to the entire report), 3 points for attendance and participation, and 6 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

What can light tell us about atoms?

4.1 Introduction

In this lab we will study light produced in gas discharge tubes. You will first familiarize yourself with operation of the software by making careful measurements of emission lines from a hydrogen discharge tube. You will then use your knowledge of spectra to identify which elements are present in several other discharge tubes.

4.2 Learning goals

- Use experimentally derived quantities to calculate the Rydberg constant.
- Identify unknown elements based on their spectra.
- Compare continuum vs. line emission.
- Demonstrate an ability to make careful measurements.
- Demonstrate proficiency in basic calculations and plotting using spreadsheets.
- Gain familiarity with a common physics tool (the spectroscope).

4.3 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.

Add members to Canvas lab report assignment group

1. On Canvas, navigate to the People section, then to the "L4 Light Atoms [number]" tab. Find a group that is not yet used, and have each person in your group add themselves to that same lab group.

This enables group grading of your lab report. Only one person will submit the group report, and all members of the group will receive the grade and have access to view the graded assignment.

4.4 Scientific background

When an electron collides with an atom in the discharge tube, the atom absorbs energy and transitions from its *ground state* to an *excited state*. When the atom later transitions back to its ground state, it emits energy in the form of light. Light from these transitions is emitted only at distinct colors, or wavelengths. The wavelengths of the spectral lines from each element are different, thus each element has it own "fingerprint" by which it can be identified. Spectroscopy can therefore be used to detect and measure elements in a material from a distance. Critically, the same lines that appear in gas discharge tubes the lab are also found in stars, allowing astronomers to study their elemental makeup. Without spectral information, there would be no other way for us to know what stars are made of because we cannot travel and take a sample, even for the closest star — our Sun.

As with much of astrophysics, we'll begin by studying the properties of hydrogen. Although hydrogen is the most abundant element in the universe, its lines in the sun are quite weak because the strength of the lines depends critically on the physical conditions in the star. Hydrogen was first identified on earth by Anders Jonas Ångström in 1853, but it was not detected in the sun until a decade later. Although Ångström was able to measure the four characteristic lines of hydrogen — known today as Hα, Hβ, Hγ, and Hδ — to a high degree of accuracy, it was not until 1885 that Johann Balmer (a sixty year old Swiss school teacher and mathematician with no physics background) found the correct mathematical relationship between the wavelengths of hydrogen. Balmer's relation suggested that the physical processes which produce hydrogen lines are connected to integer numbers, an explanation that ultimately required the overthrow of 19th century classical physics in favor of the first version of quantum theory by Bohr and others circa 1915.

The four Balmer lines correspond to transitions to the $n = 2$ state in hydrogen and follow the equation

$$\frac{1}{\lambda} = R\left(\frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2}\right) = R\left(\frac{1}{4} - \frac{1}{n_{\text{initial}}^2}\right), \tag{4.1}$$

where λ is the wavelength of a particular line and $R = 1.097 \times 10^7\,\mathrm{m}^{-1}$ is the Rydberg constant, with $n_{\text{initial}} > 2$.

4.5 Apparatus description: spectrometer

To measure spectral lines, astronomers use a device called a spectrometer, spectroscope, or spectrograph. Spectrometers used for precision scientific measurements have three basic elements:

1. A collimator consisting of a slit and mirror or lens. The collimator produces a parallel beam of light in one direction, similar to an eyepiece of a telescope
2. A dispersive grating that bends the light at an angle that depends on the wavelength of light, thereby decomposing it into a spectrum
3. A mirror or lens that collects the light and focuses it onto a detector The main part of any spectrograph is a dispersive element, which is usually a grating that consists of a very finely spaced lines etched on a substrate. The spacing between the lines can be 1/10 of the diameter of a human hair and the distance between each line is controlled to less than the diameter of a single atom. The process used to etch the grating is similar to that used in making CDs. Not surprisingly, CDs can be used to decompose a white light from a lamp into rainbow.

The angle θ at which grating reflects the light depends on the wavelength and is given by

$$m\lambda = d\sin\theta\,, \tag{4.2}$$

where m is the order of the maximum, λ is the wavelength (generally measured in nanometers, where a nanometer is 10^{-9} meters), d is the spacing of the lines on the diffraction grating (also in nm). Visible light has a wavelength of about 500 nm.

4.6 Apparatus: the digital spectrometer

A digital spectrometer also uses a diffraction grating, but instead of collecting the dispersed light on a screen to be viewed by people, it collects the light with a charge-coupled device (CCD), an array of light-sensitive pixels much like a digital camera. It then translates the position on the CCD to individual wavelengths and displays a plot of intensity vs. wavelength on a computer. Another difference is that we use an optical fiber to collect the light.

Here are a few guidelines:

- Save the images of spectra and numeric files that you generated with SpectraSuite during your experiments on a USB stick, so that you can use them at home during preparation of your report (you can also email them as attachments from your computer at the end of the lab).
- You should open a word processor document and a spreadsheet document in which you can save your measured spectra at the beginning of your work. To save an image of your graph, click on the fourth icon from the left in the Spectrum IO controls. This will copy an image of the graph to the clipboard. Then in your word processor, paste the image by pressing Ctrl-V.
- To save spectrum in the digital form, click on the third from the left icon in Spectrum IO controls (to the right of print icon). This copies it to clipboard. In Excel file make sure you are in a new sheet and press Ctrl-V. This should create to columns of numbers: wavelength (in nm) and counts for your spectrum.
- An alternative way to save the data is to click on the floppy disk icon in the Spectrum IO controls. The format must be "Tab delimiter, no header". The writing directory must be specified ("Browse" button). The spectrum is saved in a text file (.txt) as two columns, the first column giving the wavelength in nm, the second column the corresponding intensity. This file can be imported into a spreadsheet or plotting program.

4.7 Observation experiment: Spectrum of the sky and of fluorescent lamps

Goal

Observe the spectrum of the sky and of the fluorescent lights in the room, notice the differences, and identify some elements present in the fluorescent light bulb.

Rubric rows to focus on in this experiment

B5, F1, F2. See Appendix B for details.

Available equipment

- Ocean Optics Red Tide digital spectrometer with USB cable and fiber optic cable attached
- computer with SpectraSuite software
- window with daylight visible (or incandescent bulb if night-time lab)
- fluorescent light source (e.g. ceiling lights)

> **Caution: Fragile Equipment!** The fiber optic cable is a precision instrument. If it is bent in too tight a curve, it will be damaged. Do not bend these cables beyond a 12 cm radius (4.5 inches) (into part of a circle with a radius smaller than that).
>
> Also, the openings have covers to protect from dust and debris. Be sure to replace the end cover when you are done with the cable.

1. Turn on the computer and start Spectra Suite.
2. Ensure the digital spectrometer is connected to the computer and the fiber optic cable is connected to the spectrometer.
3. Remove the blue end cap from the fiber optic cable by twisting it while pulling it.
4. Press S ("Scope") to start measuring the spectrum and point the fiber towards the overhead fluorescent light. You should see live spectrum of the light entering the fiber in the graph window, which is characterized by many strong peaks (strong emission lines).

> A **fluorescent lamp tube** is filled with a gas containing low pressure mercury vapor, argon, neon, xenon or krypton, with corresponding lines in the spectrum. Emission lines are also produced by a phosphorous material (typically europium and terbium) covering the glass, after excitation by the ultraviolet emission from the lamp gas.

5. Record a spectrum and identify the different lines and their corresponding element, by comparison with other measurements of fluorescent light spectra (see Table 4.2). Save the spectrum and include it in your lab report along with markers of lines that you were able to identify.
6. Once you examine the spectrum you obtained with spectrometer, look at it with the visual spectroscope and identify lines you see visually with the lines you see in the digital spectrum.
7. Repeat the above procedure, but looking out a window at the sky. Record what you see, and make notes of how the spectrum from the sky differs from the spectrum of the fluorescent lights.

4.8 Application experiment: Measuring the Rydberg constant

Goal

Measure the wavelengths of light emitted from electrified hydrogen gas, and use those wavelengths to determine the Rydberg constant.

Rubrics rows to focus on

D4, D7, F1, F2, G2, G4. See Appendix B for details.

Available equipment

- direct viewing spectrometer
- Ocean Optics Red Tide digital spectrometer with USB cable and fiber optic cable attached
- computer with SpectraSuite software
- gas discharge lamp, hydrogen gas discharge tube

Warning: Shock Hazard! When turned on, the power supply generates 5000 V of electric potential difference across the terminals, with enough current available to injure you. Make sure that the discharge tube has its ON/OFF switch (on the side) in the OFF position when you install or change the discharge tube. If not, switch the lamp into the OFF position. Switch on the lamp to ON position only after tube is installed. The lamp will now be illuminated when the pedal is pressed. While the pedal is pressed, do not touch any part of the tube. Moving the whole unit by the base is safe.

Caution: Fragile Tube! Avoid touching the tube with your skin, as skin oils can degrade the glass over time. Wear a nitrile glove when touching a tube.

Also, the tubes have a limited lifetime of running. Turn on the tube only for as long as you need it to be on for measurement.

1. Ensure that the hydrogen tube is installed in the power supply.
2. Turn on the power supply and examine its spectrum through a direct viewing spectroscope. You should be able to see a bright magenta and a cyan line — these are the first two lines in the Balmer series. The other two lines are probably too faint for you to see; in order to measure them, we will need to use a more sensitive device.
3. Observe using the digital spectrometer by starting the SpectraSuite software, uncapping the optical fiber, and placing it as close as possible to the discharge tube and turn on the lamp. Adjust pointing of the fiber so that the height of the lines in the acquired spectrum is maximized. If the strongest lines are saturated, you can either move the fiber a bit farther away from the discharge tube or adjust integration time within the SpectraSuite software.
4. Follow these steps to measure the spectrum of light that enters the fiber using controls of the SpectraSuite software:
   a) Make sure you are in a new graph and enter Scope mode by pressing S in the controls. Point fiber at the discharge tube.
   b) Take a background "dark" measurement with the light source under study off by clicking the gray light bulb button in spectrum storage controls
   c) Subtract the background spectrum from the signal by clicking gray light bulb with minus sign button in the Processing controls. This removes contribution of background light to the spectrum.
   d) turn on the source discharge tube and record its spectrum, saving an image of it as describe above in the guidelines.
   e) While source is on, click on the spectrum graph. You should see a peak icon in the bottom right corner of the graph. This is useful peak finder: click on it and adjust controls, setting the Baseline, which is the intensity above which it will search for peaks. Peak finder identifies peaks and you can step through them and see their wavelengths using < and > buttons in the bottom left corner of the graph.
5. You should adjust the setup and acquisition time so that you can easily see four peaks (emission lines in the spectrum). Analyze the spectra and determine the wavelength of the four most prominent lines. Assume that these wavelength measurements are exact for the purposes of uncertainty analysis.

Energy level (n)	**Measured Wavelength (nm)**	**Rydberg constant (nm^{-1})**
3		
4		
5		
6		

Table 4.1: Suggested table for recording data for Step 6 in Section 4.8.

6. Write down the measured wavelengths of each line in the descending order of wavelength ($n_1 = 3$ corresponds to the peak with the longest wavelength that you measure, while $n_1 = 6$ to the shortest of the four you measure) in a table like Table 4.1. Be careful to measure the correct lines! The spectrometer is sensitive to wavelength is the near infrared and near ultraviolet, beyond detection of the human eye. Do you observe any such lines? Can they be included in your analysis?

Analysis

Using your data for each line, calculate the corresponding value of the Rydberg constant in units of 1/nm using Equation 4.1 and enter it into the column for the Rydberg constant in each line's row. The spectral lines you observe correspond to the first four transitions in the Balmer series, the transitions of electrons to the $n_{\text{final}} = 2$ level from higher energy levels.

The differences in values you get for the Rydberg constant are due to random uncertainty. To find your determination for this quantity, use your average for the value, and calculate the standard deviation for the uncertainty.

A more sophisticated way of calculating the Rydberg constant would be to plot a graph of your measurements of $1/\lambda$ vs $1/n_i^2$ and fit a straight line through it. The average value of the Rydberg constant is the slope of this line, which will be given by the slope. Carry out and present such a measurement along with the plot in your report.

4.9 Application experiment: identification of mystery elements

Goal

Identify the gas that is contained in the four tubes with colored tape on them.

Rubric rows to focus on

F1, F2

Available equipment

- Ocean Optics Red Tide digital spectrometer with USB cable and fiber optic cable attached
- computer with SpectraSuite software
- gas discharge lamp
- various gas discharge tubes with unknown gases

Helium (nm)	Argon (nm)	Neon (nm)	Mercury (nm)
389	697	585	365
447	707	594	404
469	738	614	435
492	751	627	546
502	764	640	579
588	772	651	
668	795	660	
707	801	668	
727	811	693	
	826	703	
	841	717	
	852	744	
	866		
	912		

Table 4.2: Some known emission lines of various elements.

Turn off the lamp using the switch on the side, and replace glass tube with hydrogen gas with one of the color-coded bulbs that will be provided to you. As before, use the spectrometer to acquire spectrum using the SpectraSuite software and measure wavelengths of the prominent lines (peaks in the spectrum).

Once you have measured a few prominent wavelengths, compare them with wavelengths of known lines of elements listed in the table below and identify the mystery element within the color-coded tube. Present your measurements of wavelengths in a list and a plot of the graph with several lines from Table 4.2.

4.10 Group dynamics

2. Write a 100–200 word 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? What successes and challenges in group functioning did you have? What do you want to do differently next time?

4.11 Report checklist and grading

The lab grade consists of 3 points for each of seven scientific ability rubric rows (the 5 listed above, as well as F1 and F2, applied to the entire report), 3 points for attendance and participation, and 6 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 (like Microsoft Excel, LibreOffice Calc, or Google Sheets), 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 $52 \pm 3\,\text{m}$.

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, 2π, 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 ± 0.1 km in 350 ± 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 ± 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 δa and δb 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 [1].

	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 [1].

	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 [1].

	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 [1].

	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 [1].

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.