General Guidelines

Below are general formatting requirements that apply to all assignment types and all sections. Examples for everything mentioned here can be found in the text of the example report. Keep in mind, your TA may have additional formatting or content requirements!

Heading

- Assignment must include a heading with a title and author's names

Paragraphs

- Assignment should be written as if the reader is unfamiliar with the experiment or context
- Assignment should be written in third person perspective
- In describing actions previously taken, past tense should be used
- All content should be in sentences, a table, an equation, or a figure - no bullet points or lists
- All data reported in sentences should still include units and error when appropriate

Plots & Tables

- Plots and tables need figure (plot) or table numbers with a descriptive caption
- Plot axes must be labelled with title and units
- Plots that include multiple data sets must include a legend with labels to distinguish them
- Table rows/columns must be labelled with title and units
- Tables should be formatted as tables with borders, not a screenshot of a spreadsheet

Figures

- Figures need figure numbers with a descriptive caption

Equations

- Equations must each be on their own line and formatted as an equation
- Variables used in equations must be defined

References

- Any preferred reference system that is consistent and clear is fine (IEEE, APA, MLA, etc.)

Example Report[1] – Hooke's Law

Author Names
General Physics I | IU Indianapolis | Fall 2024

Introduction

Introduction Guidelines	**10 %**
This section gives some background on the major ideas and context necessary to understand the experiment, particularly for an unfamiliar reader. Should at least include (1) qualitative definitions or explanations for the biggest concept(s), (2) the significance, history, or application of the experiment and its subject, and (3) the objective of the experiment.	

The objective of this example lab was to determine the spring constant of a given spring using two different methods: first utilizing Hooke's Law (Activity 1), and then again utilizing simple harmonic motion (Activity 2).

Springs are many a physicists' favorite toy, and for good reason; they have a myriad of characteristics that make springs unique and interesting. One of those characteristics is the *spring constant*, usually denoted by the letter k. The spring constant can be loosely considered as a measure of 'how hard' the spring is to stretch or compress, the spring constant is unique to each individual spring. Physicists have long used springs (and spring constants) as inspiration for modeling many different systems that exhibit simple harmonic motion – in fact, often the bonds between atoms in molecules are described in terms of springs due to internal vibrations.

Theory

Theory Guidelines	**15 %**
This section is a description of all theory, concepts, and equations necessary to understand and analyze your data.	

[1] This *example* lab report is meant to provide you with a visual representation of what a lab report should look like. **This example is not representative of the content you will be expected to include for your own lab reports.**

This should at least include (1) all equations used in your analysis, (2) the meaning of each variable in those equations, (3) statements of about any assumptions or limitations of the equations, and (4) descriptions of how each equation is used in your analysis and how the equations connect to one another.

A diagram is also often useful in this section to clarify how the variables you're using relate to the system you're studying.

When describing the behavior of springs, we often begin using Hooke's Law (introduced by Robert Hooke[2] in 1678). Hooke's Law describes the elongation of a spring as being proportional to the force added onto the spring. Or rather, in equation form, Hooke's Law looks like:

$$F_s = -kx, \tag{1}$$

where F_s is the force on the spring, k is the spring constant, and x is how far the spring as elongated or compressed. The negative sign is important, not because it indicates a specific direction (i.e., it doesn't mean the force is always *down*), but because it indicates the force is always pointing *away* from the direction of elongation/compression. This is because the spring force is considered a *restoring force*. The spring wants to be in a state of *equilibrium* where the forces are balanced and there is no net force on the spring. When a net force is added ($F_s \neq 0$), the spring will stretch/compress into a new equilibrium state.

Now, consider a spring that is suspended from a rod so that it is allowed to stretch under the force of gravity. Without adding any weight to it, the spring will naturally elongate under the force of its own weight and rest at an equilibrium position. If we add mass to the bottom of the spring, it will increase the force of gravity on the spring, causing it to elongate to a new equilibrium position. Activity 1 of this lab explores doing just that and using the data to find the spring constant. However, if instead of allowing the spring to come to a rest, we intentionally stretch the spring past its equilibrium point and then let it go. The restoring force described in Equation 1 would pull the spring up, but the momentum of the spring would carry it past its equilibrium point and cause the spring to compress, at which point it would come to a rest and then the force of the spring would cause it to fall once again toward the equilibrium point. At this point, the spring would begin to exhibit *simple harmonic motion* (SHM), where the spring begins to *oscillate* around its equilibrium point.

Thankfully, we are able to describe the position of objects in SHM using the following general wave equation[3]:

$$x(t) = A\cos(\omega t + \varphi), \tag{2}$$

[2] Hooke published this law in 1678, and if anyone is looking for some fun physics-related drama, I encourage you to read about his ongoing rivalry with Sir Issac Newton (it's as juicy as some Desperate Housewives stuff).

[3] This is a condensed form of the general equation useful for this lab, but there is a more complete form that includes a sine term. The Wikipedia for SHM does a reasonable job at explaining this: https://en.wikipedia.org/wiki/Simple_harmonic_motion

where *x(t)* is the position as a function of time, *A* is the amplitude, ω is the angular frequency (not to be confused with simply the frequency: ω = 2π*f*), *t* is the time, and φ is the phase. While Equation 2 does a great job at explaining the position of the spring as it oscillates, it does not yet directly allow us to relate the SHM of the spring to its spring constant.

Without going through the details of the derivation (though anyone interested is highly encouraged to do so), the acceleration of the spring can be found as a function of time by taking the second time derivative of Equation 2, resulting in:

$$\frac{d^2x(t)}{dt^2} = a(t) = -A\omega^2\cos(\omega t - \phi). \qquad 3$$

At time *t*=0, and assuming the initial phase is also 0, the cosine vanishes from Equation 3, and the acceleration is a maximum. Coincidentally, this also indicates that the acceleration is dependent only on the maximum amplitude. If we set the maximum amplitude to be the amount the spring is compressed/elongated, then Equation 3 condenses very neatly to

$$a(x) = -x\omega^2. \qquad 4$$

It's worth noting at this point that the goal of this derivation is to eventually find a way to relate the SHM of a spring with its spring constant. While Equation 4 doesn't do that directly, what it does do is give us an expression for the acceleration *at any point*. This is good news, as it allows us to relate Equation 4 with Equation 1. First, we can get the force on the spring by multiplying Equation 4 by the mass, such that

$$F_s = ma(x) = -mx\omega^2. \qquad 5$$

Then we can directly set Equation 5 and 1 equivalent:

$$-mx\omega^2 = -kx, \qquad 6$$

which, after some rearranging, yields:

$$\omega^2 = \frac{k}{m}. \qquad 7$$

Equation 7 gives us exactly what we were looking for: a way to relate SHM to the spring constant. However, ω is a little tricky to directly measure, so a more convenient representation of Equation 7 can be found by using the definition of ω as: $\omega = 2\pi f$, where *f* is the time-interval frequency measured in Hertz. By doing so, Equation 7 becomes:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \qquad 8$$

but again, the frequency is a little annoying to measure directly, so we can at advantage of the definition of *periodic* motion where the *period of the motion, T,* can be given as: $T = 1/f$. Equation 8 then becomes:

$$T = 2\pi\sqrt{\frac{m}{k}}. \qquad 9$$

It is Equation 9 that gives us exactly what we want. We can relate the *period of oscillation, T,* with the spring constant, *k*. Activity 2 of this lab utilizes Equation 9 to relate measurements of the period with the mass on the spring in order to find the spring constant.

Procedure

Procedure Guidelines **10 %**

This section is a detailed description of how data was collected and analyzed. A reader should be able to read this section along and repeat everything about your experiment precisely as you did it!

It should at least include (1) all tools and equipment used and their arrangement, (2) all parameters measured directly, and the tools used to measure them, (3) all parameters varied across measurements and all the tested values, (4) all software tools or calculation methods used to analyze data.

A diagram of your experimental set-up with labels for the equipment is also often useful in this section to clarify how the measurements are being taken.

For this lab, the following equipment was utilized: a meter stick, triple beam balance, two stopwatches, spring of unknown spring constant, ring stand with bar for holding spring, mass set, and a computer with Microsoft Word and Excel.

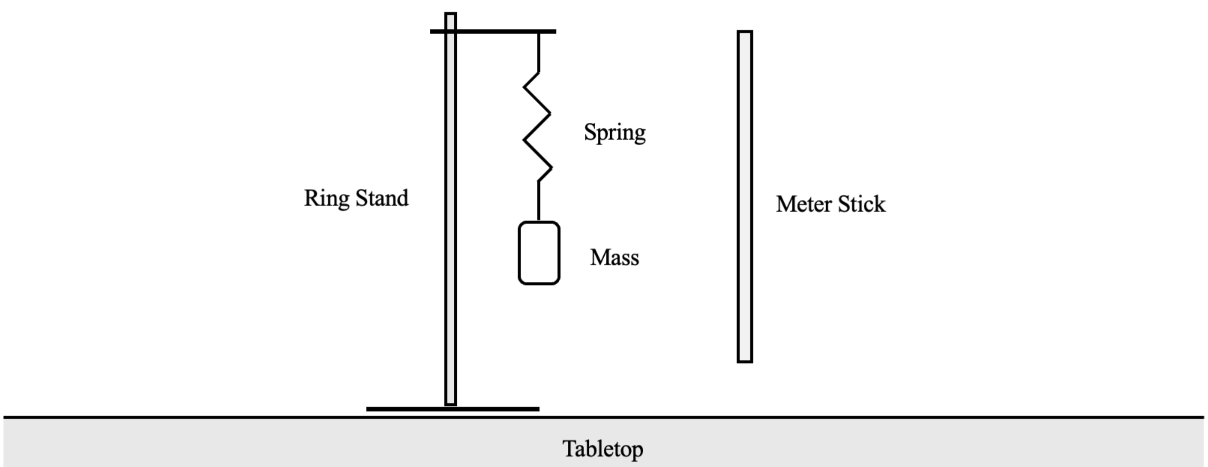


Figure 1: Experimental Diagram

Activity One:

In activity one, we began by measuring the mass and unstretched length of the spring. The unstretched length will provide a baseline for measuring the displacement of the spring. The spring was then affixed to the ring stand and was allowed to stretch and rest to a new equilibrium point. This stretched length was then measured by each partner. The mass of a slotted-mass hanger was then measured and affixed to the bottom of spring. Once the spring stretched and came to rest, the displacement was measured (again, by each partner). A slotted mass of 20 grams was then added to the mass hanger and the displacement was measured again. This same process was repeated for a total of 5 different masses. From the masses, the spring force was found for each mass value, and then a plot of the force vs elongation was generated, allowing for the spring constant to be found from that plot.

Activity Two:

Beginning with the same setup from Activity 1, the mass hanger was affixed to the bottom of the spring. The spring was then pulled straight down vertically ~10cm, and this value was the same for each trial/mass. The partner holding the spring counted down and released the spring, so that it exhibited simple harmonic oscillations. Each partner began a stopwatch when the spring was released, and after 10 complete cycles, the stopwatches were stopped. From the data, the average time for one cycle was found for each partner, and then averaged together for one value per mass. Fifty grams was then added to the mass hanger and the process was completed again. This same process was then repeated for a total of five different masses. The period (T) values were then squared, a plot of T^2 vs mass was generated. From this plot, the spring constant was found.

Analysis

Analysis Guidelines	**30 %**

This is the big one. This section is all about stating the results of your experiment in detail, giving them context, describing the analysis you performed, and stating the results of that analysis in detail. Essentially: what did you measure, what did you do with it, and what did you find?

This should at least include: (1) all experimental results (raw data or summaries of it) in value, plot, or table form, (2) descriptions of the analysis process used to make sense of that raw data, (3) all analysis results in value, plot, or table form, (4) error values or error bars on all results when relevant along with description of what that error represents experimentally.

The above gives general types of content that will be included in this section for most experiments, but always look at the experiment handout for more details about the results and analysis you need to include for a specific experiment.

Table 1: Spring data[4].

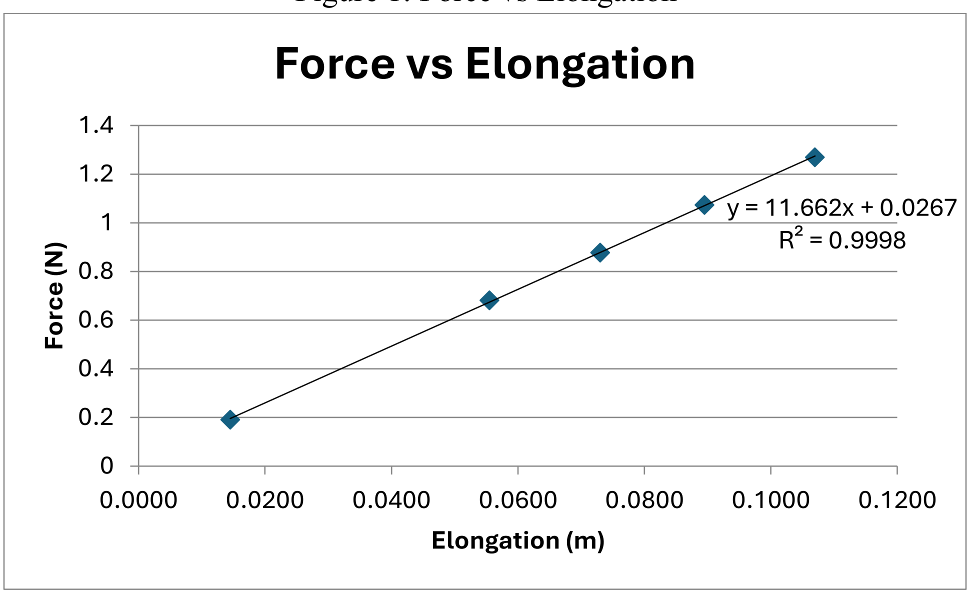
Spring Data			
Mass (kg)	σM (kg)	Unstretched length (m)	σL (m)
0.05860	0.00002	0.1100	0.0002

Table 2: Force and Elongation data for Activity 1.

Activity 1								
Mass (kg)	Fg (N)	x (m)		Δx (m)		Δx_avg (m)	σx (m)	x_se (m)
		Partner 1	Partner 2	Partner 1	Partner 2			
0.01953	0.1914	0.1247	0.1243	0.0147	0.0143	0.0145	0.0003	0.0002
0.06953	0.6814	0.1650	0.1660	0.0550	0.0560	0.0555	0.0007	0.0005
0.08953	0.8774	0.1825	0.1835	0.0725	0.0735	0.0730	0.0007	0.0005
0.10953	1.0734	0.1990	0.2000	0.0890	0.0900	0.0895	0.0007	0.0005
0.12953	1.2694	0.2165	0.2175	0.1065	0.1075	0.1070	0.0007	0.0005

In Table 2, F_g was determined by finding the force of gravity of the mass on the spring (i.e., F_g = mass *9.8m/s^2), x is the total length of the spring, Δx is the displacement found by subtracting the equilibrium length with no mass from Table 1 from each x value, Δx_avg is the average displacement, σx is the standard deviation of the displacement values, and x_se is the standard error of the displacement values.

Figure 1: Force vs Elongation



[4] Note that the symbol σ denotes the uncertainty in the measurements as estimated using a generic 20% of the smallest division. Uncertainty for all length measurements was estimated to be +/- .02cm and for all mass measurements was estimated to be +/- .02g.

Figure 1 is simply the data from Table 2 graphed visually. The x-axis is the elongation and corresponds to the "Δx_avg" column in Table 2. A linear trendline was applied, and the resulting equation and R^2 value are given. A linear trendline was chosen as the spring equation (Equation 1) suggests a linear relationship between the force and elongation. In a linear equation, the slope is considered constant, and by comparing a linear equation to the spring equation, in this case, the slope is the spring constant. Each data point includes the standard error as an error-bar, but they are much too small to show up.

While there is nothing inherently wrong with Figure 1, it does show a nonzero y-intercept. This makes no real physical sense, as the expectation would be that with no mass, the force and subsequent elongation would be zero. One could make the argument that the y-intercept value would be the force on the spring itself, but the first value is the measurement with just the spring (adjusted for the effective mass) itself. This would indicate that we have a pretty solid conceptual rationale for forcing the plot through zero.

Figure 2: Force vs Elongation for a y-intercept of 0.

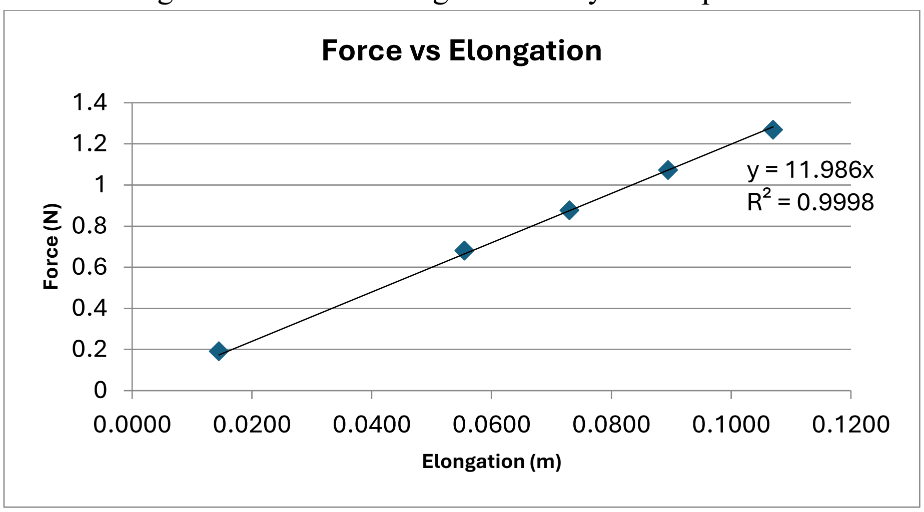


Table 3: Mass and Period data for Activity 2

Activity 2							
Mass (kg)	Total Time (s)		Period (s)		T_avg (s)	σT (s)	T_se (s)
	Partner 1	Partner 2	Partner 1	Partner 2			
0.06953	4.80	4.76	0.480	0.476	0.478	0.003	0.002
0.11953	6.00	5.96	0.600	0.596	0.598	0.003	0.002
0.16953	7.54	7.48	0.754	0.748	0.751	0.004	0.003
0.21953	8.47	8.43	0.847	0.843	0.845	0.003	0.002
0.26953	9.40	9.34	0.940	0.934	0.937	0.004	0.003

Table 3 includes the period data for Activity 2, including the standard deviation and standard error for each of the period measurements. However, in order to graph something useful to allow us to find k from this dataset, we can square both sides of Equation 9 to arrive at

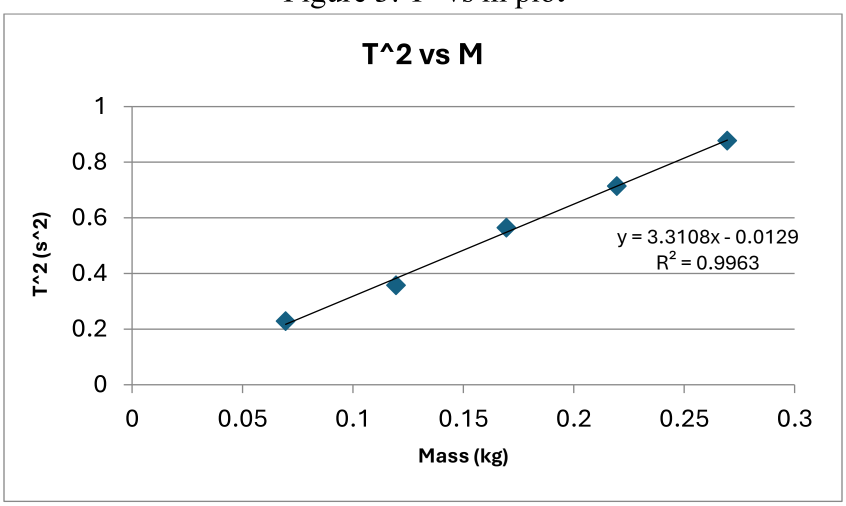
$$T^2 = \frac{4\pi^2}{k}m. \tag{10}$$

Equation 10 now tells us we need each period value from Table 3 squared. The results of this are shown below in Table 4:

Table 4: Activity 2 data with the period squared

Act 2	
Mass (kg)	T^2 (s^2)
0.06953	0.228
0.11953	0.358
0.16953	0.564
0.21953	0.714
0.26953	0.878

Figure 3: T^2 vs m plot



It's not as immediately clear for Figure 3 as to if it should also be forced through (0,0) like Figure 2. This is because the y-intercept here tells us the mass that would require the period to be 0s. Well, if we consider the only possibility that the period would be zero in Equation 10 would have to be if the mass is also zero, that gives a reasonable indication that this Figure 3 could also conceptually be forced through (0.0). To that end, Figure 4 below replots the data in Table 4, but forces the graph through zero.

Figure 4: T^2 vs m plot (forced through origin)

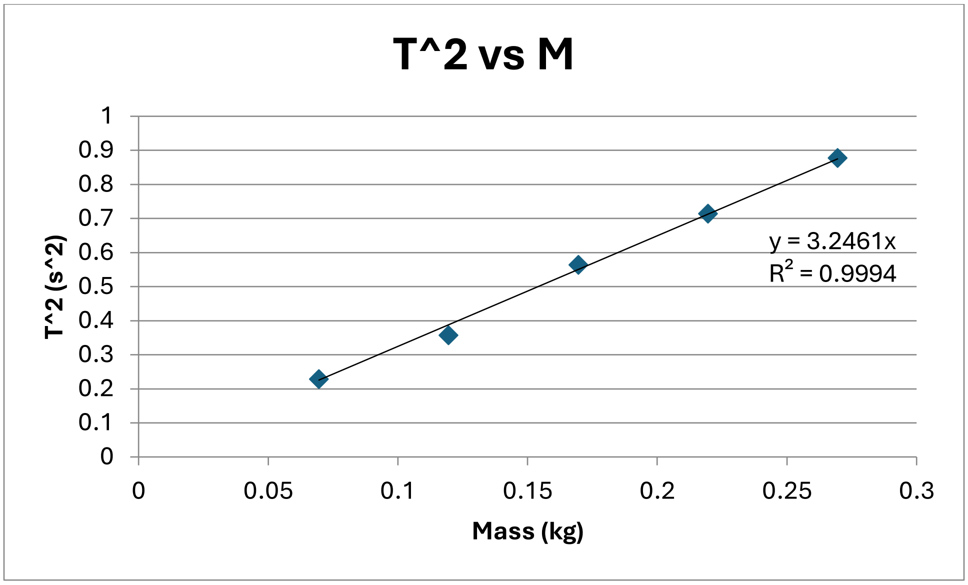


Table 5: Summary of Results

Summary Table				
k (N/m)		σK (N/m)		% diff
Act 1	Act 2	Act 1	Act 2	
11.66	12.16	0.09	0.15	4.198

The uncertainty in the spring constant for both activities was found using the LINEST tool in Excel and applying it to the data from Figures 2 and 4, respectively. An important note to make is that both values were found while forcing the y-intercept value to be zero. It is also worth noting that each plot above includes the standard error as error-bars on each value, but they are much too small to show up.

Discussion

Discussion Guidelines	25 %
This section is all about taking the results you reported and making sense of them. What trends are demonstrated, do they align with what you expected, and why?	

This should at least include: (1) discussion of all relevant relationships and trends you determined between the parameters involved, (2) the success of your experiment in achieving its objective based on these results (do they agree or disagree with predictions, known values, etc.), (3) validation for correct/consistent results or reasonable explanation for incorrect/inconsistent results, (4) sources of error, ways to improve the procedure, and potential future experiments.

The above gives general types of content that will be included in this section for most experiments, but always look at the experiment handout for more details about the discussion you need to include for a specific experiment.

In Activity 1, we used Hooke's Law to measure the spring constant of a spring by relating the force on the spring to how far the spring stretched. We found a spring constant of 11.66 +/- .09 N/m as the spring constant for the first activity. This was done by suspending a spring vertically from a ring stand and adding mass to the spring while measuring how far the spring was stretched. A plot of the force vs the elongation of the spring was generated, and an argument was made for forcing the plot through zero (Figure 2). From there, the slope was found and, by relating the equation of a line with Equation 1, the slope was determined to be equivalent to the spring constant, allowing for a direct measurement of the spring constant from Figure 2. The uncertainty was found to be +/- 0.09 N/m as determined from the LINEST tool.

Activity 2 utilized Equations 9 and 10 to measure the spring constant while the spring was exhibiting simple harmonic motion (SHM). In activity 2, the spring constant was found to be 12.16 +/- 0.15 N/m. Masses were added to the bottom of a vertically suspended spring which was stretched ~10cm each time and then released. The periodic motion was then measured using stopwatches. A plot of T^2 vs the mass was generated and similarly to Activity 1, a second plot was made which forced the y-intercept through the origin (Figure 4). Comparing the linear equation with Equation 10 leads to the interpretation of the slope in Figure 4 to be equivalent to $\frac{4\pi^2}{k}$, and after some rearrangement, the spring constant was found to be 12.16 N/m. The uncertainty was found to be +/- 0.15N/m, though the determination of this uncertainty was slightly more rigorous through the method of error propagation.

Unfortunately, while the two values from each activity are within <5% (~4.2%), they are not in agreement with one another as neither value fits within the other's boundaries. That is to say, the maximum value from Activity 1 would be ~11.75 N/m, while the minimum value from Activity 2 would be 12.01 N/m. Because of this lack of overlap, while the two values are close, they do not agree with one another.

This disagreement could be due to a myriad of potential errors. In Activity 1, the uncertainties for the length and mass measurements were deliberately chosen to be 20% of the smallest division to account for estimation errors between tick marks on the meter stick and/or the triple beam balance. Additionally, while length measurements should be made to the same point each time, there could have been slight deviations each time, resulting in random errors.

There was an assumption made for the sake of time that the values printed on the masses added to the mass hanger were accurate, and this assumption could be invalid. While the generic 20% rule could account for this deviation, a simple solution of measuring the masses could have given a more accurate mass and more representative uncertainty.

Activity 2 had its fair share of errors as well. While there is some carry-over from Activity 1 (e.g., the mass assumption), there are others specific to Activity 2 that could account for the higher error bounds in that activity. First, there is a reliance on students getting time data. This means stopwatches were used where partners had to start and stop the stopwatches at certain intervals. This method relies heavily on reaction times, so the stopwatch may not have been started exactly when the hanging mass was released or stopped at exactly the tenth complete cycle. This could have shortened or lengthened the period values. Additionally, there is a clear outlier in both Figures 3 and 4, and this is the second data point. It appears to be significantly lower than the remaining values, so it is likely that a random error (such as possibly pulling down further than 10cm) occurred to cause a lower value. On a related note, it is almost impossible to pull the hanging mass down exactly 10cm each time, so it's likely that could be a source of noise in the data. Additionally, while the motion for the spring was intended to be only in one dimension (vertical), there is a distinct probability that the motion could have also been in the horizontal direction as well, which would have an impact on the stability and path of the spring.

Despite this myriad of potential errors, the values for the spring constant from each activity are only ~4.2% different from one another. So, while the values currently do not agree with each other, this is likely due to the relatively small uncertainties attached to each rather than a fundamental difference in the methods. That said, the relative opportunities for error seem to be greater in number for Activity 2, which is reflected by the higher uncertainty in the value of the spring constant. A photogate in Activity 2 could dramatically reduce the number of potential errors (such as reaction time), which could lead to better results. Additional trials with more masses could also improve the overall fit of the line too, and could help bring the values from each activity closer in line with one another.

Care & Professionalism Guidelines	**10 %**
This last section isn't content you'll include in any submissions, but it is a grading category. This category is all about the intentionality and care you display in the way your submission is written. Basically, all content should be simple to find and easy to read! No specific headings, fonts, margins, or other factors are specifically required, but the structure, format, and content must work together such that (1) all information is present and is organized clearly and logically, (2) nothing is overly distracting or difficult to read, and (3) spelling, grammar, and punctuation are acceptable.	