A. Laboratory Instructions

The laboratory work in General and University Physics is designed to:

1. Acquaint the student with scientific laboratory techniques,
2. Correlate the academic work of the classroom with actual laboratory experience,
3. Develop problem-solving skills,
4. Give practice in drawing scientific conclusions, and
5. Show the close relationship between science and mathematics and to help the student gain facility with this most important tool.

The laboratory work is scheduled in the order given in the Laboratory Schedule on the Class Web Page. Each student will consider the next assignment, and study the procedure and theory before coming to the laboratory. Reference materials, laboratory manuals, the text, etc. should be freely used. Some of laboratory experiments will be accompanied with pre-lab quiz and/or online activity. The completion of this quiz and/or activity is required in order to start the lab.

All data taken in the laboratory must be recorded on laboratory note paper in a neat, orderly fashion with proper headings for rows and columns of figures. The correct units must always be given. It is your responsibility to turn in the carbon copy of your data sheet at the end of each lab period.
A.1 Submission of Results

A formal report is required of each student, unless otherwise is announced in class. Reports are usually due at lecture time four days after the experiment. One of the lab reports will be written up collectively and the results will also be presented orally.

The Report

Reports may not be accepted if turned in later than the due date unless a reason is given that satisfies your instructor; late reports are penalized by a reduced grade. They must be typed and will be judged based on proper English usage and on scientific content. The report should, in general, contain the following items:

(Document header) Lab title, author/collaborator list, date performed.

- **Abstract**: A simple statement of the objectives of the experiment. Followed by a single comment about how well those objectives were met Try to cite one or two numbers and their uncertainties as evidence for your conclusions.

- **Equipment/Apparatus**: List of equipment used, not including pens, pencils, calculator, or Excel spreadsheet. Describe the context of the use, a drawing or picture of equipment that is not obvious to those who were not present, and an image of how it all fits together (if appropriate).

- **Theory**: Start with repeating the objective listed in the abstract. Then explain what the theory (big picture) predicts will happen (and why) for the set of measurements you will perform. Use equations to connect measurements to final results and comment on expected values for the result. If the result will be found from a graph, explain what the slope and intercept mean physically. Finish by stating the criterion by which you can judge if the experiment verifies or does not verify the theory.
- **Technique/Procedure:** Give a brief outline of the procedure of the experiment, pointing out how the uncertainty is estimated for the specific measurements and building a context for the objective. *This must be in your own words*, not copied or even transposed from the instruction sheets or from other laboratory manuals. Refer to the Equipment section as appropriate. The point of these sections is to be able to find the equipment and verify your measurements at a later date.

- **Data:** Provide a neat table of measured and calculated data including uncertainties. Show how calculations were performed. As appropriate, a graph of the data must be given. If you are using MS Excel to analyze your data, the electronic copy of your Excel data file is acceptable as the Data section of your report. The original data sheet must have been turned in at the end of lab.

- **Analysis:** Analyze your data. Describe important patterns of the data, such as: Is the graph linear or quadratic? What are the slope and intercept (including units)? Is your result consistent with the theory? How so? Cite uncertainty or %-uncertainty as applicable. Cite %-error or %-difference as applicable. Give a *quantitative* statement of the sources of uncertainty and their effect on the results of the experiment. Which measurement introduced the most uncertainty? Explain how you minimized the uncertainties.

- **Results and Conclusions:** A brief discussion of what you can conclude about the initial assumptions and objectives based on the analysis. Reference the theory section as appropriate. Cite the relevant results from your analysis which support your conclusion. How do the data support your conclusion?

The special grading rubric will be provided to clarify the Lab Report grading procedure.

**A.2 The Presentation**

Once during the semester, the lab groups will present their results orally as well as writing a report. Labs will typically consist of groups of three. During a three-hour presentation-lab, each of
the three students will have 7-10 minutes to present a section of their oral report. After each group presentation, questions may be asked of the group for up to 5 minutes. The trio will receive a single grade based on all three presentations. The special grading rubric will be provided to clarify the Oral Presentation grading procedure.

Presentation Guidelines

- **General Guidelines**
  - Form groups of 3 ±1
  - Each group will present an oral report and a written report (detailed below)
  - You must notify us one week before presenting about the equipment you will need (Overhead projector, Power-Point display, etc)

- **Oral Report**
  - The oral report grade will count as one lab score
  - The order of group presentations will be drawn at random
  - Each group has 30 minutes to present
  - Each member of the group must give a portion of the presentation
  - Each person must speak from 5 to 10 minutes
  - Extra Credit will be given for good questions from the audience (for a good question and for a good response).

- **Written Report**
  - Each group must submit a single, jointly-written report
  - List authors in order of contribution (as decided by the group)
  - Recommendation: Each group-member should write the reports during the week that the lab is performed as if you were turning in the standard weekly report. Combine these into the final single report.

**A.4 Uncertainty: Measuring Precision**

The *true value* of a physical quantity is almost never known exactly. Several determinations of a quantity can be made using the same apparatus, with differing results. Sometimes the accuracy
with which a given measurement can be made is determined by variations in the thing being measured. For instance, a number of measurements of the diameter of a baseball would probably show that the ball is not a perfect sphere and consequently the measured values would be distributed over a range of values.

Sometimes the accuracy with which a measurement can be made is determined by the accuracy with which the scale on the instrument can be read. For example, it is hardly possible to read a meter stick more closely than ± 0.5mm. The limits of accuracy may be set either by the precision of the scale of the instrument or by the ability and/or skill of the observer. But limits always exist.

It is also possible to have systematic error due to faulty instruments, for example, a meter stick which is not exactly one meter long. Then all measurements made with the instrument are in error, usually by a constant factor.

Uncertainty is not the failure of the observer to read the instruments correctly. If the observer records a 99.5 when the value should have been 89.5, this is not uncertainty, but is a mistake.

It is always of interest and usually necessary to know just how dependable are the results of an experiment and it is usually not the absolute uncertainty that is important but the percent uncertainty between the measured value and the "true" value (a.k.a. the "accepted value").

\[
\text{%-uncertainty} = \frac{\text{uncertainty}}{\text{accepted value}} \times 100\%
\]

For example, a 1000 km uncertainty in measuring the distance from Abilene to Moscow is much worse than a 1000 km uncertainty in measuring the distance from Abilene to the Sun.

When an accepted answer exists, the percent error is calculated from the difference divided by the accepted value:

\[
\text{%-error} = \frac{(\text{accepted-experimental})}{\text{accepted}} \times 100\%
\]

The percent difference is calculated between two experimental values from the difference divided by the average (which is your best guess at the true value):

\[
\text{%-error} = \frac{(\text{value#1-value#2})}{\left(\frac{\text{value#1}+\text{value#2}}{2}\right)} \times 100\%
\]
A.5 Propagation of Uncertainty

Along with knowing the percent difference between two numbers, it is also necessary sometimes to know whether two numbers are consistent, i.e., is it possible for the numbers to be equal to each other if the uncertainties on the numbers are taken into account. For example, suppose the "true value" is 20, but your experimental result is $17 \pm 3$. At first glance we can say that 17 does not equal 20, but since the actual range of the result is from 14 to 20 (i.e., 17 plus or minus 3), it very well could be equal to 20. If this is the case, we say that the experimental result and the true value are consistent. If the experimental result was $15 \pm 3$, we say it is inconsistent with the true value. Therefore, it is essential to know the uncertainty range (A.K.A. margin of error, or error-bars) on your experimental results. This is how you tell whether your answer is "good enough" or not.

The uncertainty range on an experimental result depends on the uncertainties of all the measurements that were made during the lab leading up to this result. Taking these various measurement uncertainties and determining the uncertainty range on the final answer requires a process known as Error Propagation. One result of error propagation is that the various experimental uncertainties always combine to increase the overall uncertainty. For example: suppose measurements of the length of two pieces of string are made, with the goal of knowing their combined length. If the first piece is measured to be $10 \pm 1$ cm and the second is measured to be $5 \pm 1$ cm, the total length is 15 cm, but the overall uncertainty is $\pm 2$ cm. The 1 cm uncertainty on each measurement added to give a combined uncertainty of 2 cm.

Notice that the first string can be no shorter than 9cm and no longer than 11cm ($10 \pm 1$ cm). Similarly, the second string can be no shorter than 4cm and no longer than 6cm ($5 \pm 1$ cm). Therefore, the combination can be no shorter than 13cm and no longer than 17cm: $15 \pm 2$cm.

The above simple example dealt with what will be called the uncertainty. Another way to express uncertainty is the percent uncertainty. This is equal to the uncertainty divided by the measurement, times 100%. For example, the percent uncertainty from the above example would be $\left( \frac{1cm}{10cm} \times 100\% = 10\% \right)$ and $\left( \frac{1cm}{5cm} \times 100\% = 20\% \right)$. In some cases of error propagation the
uncertainties are used and in other cases, the percent uncertainties are used. The rules for
determining which to use are given below:

1. When two measurements with associated uncertainties are added or subtracted, the overall
   uncertainty is equal to the sum of their uncertainties.
2. When two measurements with associated uncertainties are multiplied or divided, the overall
   percent uncertainty is equal to the sum of their percent uncertainty.

Example:

The area and perimeter of a rectangular table are to be calculated. The table is measured to be
176.7 cm±0.2 cm along one side and 148.3 cm±0.3 cm along the other side. Because the perimeter
is found by adding the sides, rule 1 is used:

\[ P = 176.7\,cm + 148.3\,cm + 176.7\,cm + 148.3\,cm \]
\[ P = 650.0\,cm \]
\[ \Delta P = 0.2\,cm + 0.3\,cm + 0.2\,cm + 0.3\,cm \]
\[ \Delta P = 1.0\,cm \]

The perimeter is \( P = 650\,cm \pm 1\,cm \). The area of the table is calculated to be (significant digits are
underlined)

\[ A = 176.7\,cm \times 148.3\,cm = 26204.61\,cm^2 \]
\[ \Delta A = \frac{0.2\,cm}{176.7\,cm} \times 100\% + \frac{0.3\,cm}{148.3\,cm} \times 100\% \]
\[ \Delta A = 0.11\% + 0.20\% = 0.31\% \]

Since 0.31%\( \times 26204.61\,cm^2 = 82.67\,cm^2 \), we write the area in a variety of ways:

\[ A = 2.620 \times 10^4\,cm^2 \pm 0.3\% = 2.620 \times 10^4\,cm^2 \pm 0.008 \times 10^4\,cm^2 = 2.620 (8) \times 10^4\,cm^2 \]

Please be aware that the reason some digits are called insignificant is that they are insignificant:

0.31548%\( \times 26204.61 = 82.67 \)
0.31%\( \times 26204.61 = 82.23 \)
0.31%\( \times 26200 = 81.22 \)
0.3%\( \times 26204.61 = 78.61 \)
0.3%\( \times 26200 = 78.60 \)

All of these round to 80\( cm^2 \), giving

\[ A = 2.620 \times 10^4 \pm 0.008 \times 10^4\,cm^2 \]
A.6 Periodic (Cyclic) Behavior

When any object moves with a pattern which repeats at regular time intervals, it can be described as "oscillating" and is said to be in periodic motion. This applies to pendulums swinging, clock-hands whirring, merry-go-rounds spinning, water-waves undulating, sound waves, light-waves, radio-waves, a heart-beat, etc. Regardless of the object in motion or the type of motion, there are a few terms which are appropriately applied.

The period $T$ is the amount of time elapsed during one oscillation. (Periodic motion is motion which has a period.) The units are seconds-per-oscillation; although you may also see them as minutes-, hours-, or days- (among other possibilities) per oscillation.

Aside:

*Despite these units being a time per oscillation, it is often treated as a straight time interval; the number of oscillations in that case is assumed to be 1. Technically the period is not simply a time, but the time is found by multiplying the period by the quantity 1 oscillation. So, the conversion is easy to do in your head.*

Numerically, a large period indicates more time per oscillation, which describes slower motion.

The frequency, $f$, is the rate of oscillation: the number of oscillations during some time. The frequency is the reciprocal of the period, $f=1/T$, and has units of oscillations-per-second. Numerically, a large frequency (a small period) indicates more oscillations during some time, which describes faster motion.

The angular frequency (or angular velocity), $\omega$ is another related term. This is generally reserved for circular motion, but can be applied to periodic motion as well. The difference between the frequency and the angular frequency is that the angular frequency is measured in radians-per-second rather than in oscillations-per-second. Radians are considered a unitless dimension -- the natural measure angle. There are $2\pi$ (radians) in $360^\circ$ (which is one full circle/oscillation). So, we convert from frequency to angular frequency via
\[ \omega = \frac{2\pi}{\text{losc}} \quad f = \frac{2\pi}{T(\text{losc})} \]

Notice that in the second equality, we see the product of the period and 1 oscillation. This is the time (measured in seconds) of one oscillation. The units of \( \omega \) are \`reciprocal seconds\' (1/s).

Your pulse is generally measured in beats-per-minute. This is a frequency.

**Measurements of These Quantities**

In order to measure the any of these quantities, we need to time it. We obviously don't need to measure both the frequency and the period since we can easily find one from the other. These variables are measuring the same relationship, but expressing it differently. We need to decide on the convenience of when to stop counting. You can either measure the period by timing a specified number of oscillations or you can measure the frequency by counting the oscillations during a specified amount of time.

If you count the number oscillations during a specified amount of time, you must worry about the final fraction of an oscillation. In the following example, you will notice that we ignore the initial and final fractional beats. This adds to the uncertainty. (We have assumed it is \( \pm 1 \) beat, but it could easily be \( \pm 2 \) beats, depending on the timing of our start and stop times.)

**Example:**

When your pulse is taken, it is often taken for ten or fifteen seconds and extrapolated to a minute. It is possible to take my pulse for one minute. In doing so, you may count 15 beats in the first ten seconds (\( \approx 90\text{beats/min} \)). If you continue, you might find 29 beats after twenty seconds (\( \approx 87\text{beats/min} \)). Perhaps then you see 43 beats after thirty seconds (\( \approx 86\text{beats/min} \)).

The problem here is that extrapolation is intrinsically imprecise. If we track the uncertainty of the first measurement,

\[
\frac{15 \pm 1\text{beats}}{10\text{sec}} \approx 1.5 \pm 0.1 \text{beats/sec} \times \frac{60\text{sec}}{1\text{min}} = 90 \pm 6 \text{beats/min}
\]

On the other hand, if you count for 20 sec, then you find
These numbers are consistent, but the second is more precise. We cannot say at this point which is more accurate because we do not know the true solution. One more time:

\[
\frac{29 \pm 1 \text{ beats}}{20 \text{ sec}} \approx 1.45 \pm 0.05 \text{ beats/sec} \times \frac{60 \text{ sec}}{1 \text{ min}} = 87 \pm 3 \text{ beats/min}
\]

\[
\frac{43 \pm 1 \text{ beats}}{30 \text{ sec}} \approx 1.43 \pm 0.03 \text{ beats/sec} \times \frac{60 \text{ sec}}{1 \text{ min}} = 86 \pm 2 \text{ beats/min}
\]

The obvious trend in this example is that longer measurements correspond to more precise results. Therefore, when measuring a period (or a frequency) you should consider long time intervals. As mentioned above, we should also worry about fractional oscillations when measuring a frequency.

On the other hand, if we measure the period, then we can use the precision of the clock and measure whole oscillations. In doing this, we ought to measure the time for many (greater than 20) oscillations and divide that time by the number of oscillations. The more oscillations which are averaged over in this manner, the better, because your timing-uncertainty is divided by the number of oscillations as well. Furthermore, you have reaction-time uncertainty at the beginning and at the end. To minimize this effect we should make these 2 oscillations a small percentage of our total oscillations: 2 is 20% of 10 oscillations, is 10% of 20 oscillations, and is 1% of 200 oscillations.

Additional improvements can also be made by repeating the measurement two or three times.