ARIZONA STATE UNIVERSITY

GENERAL STUDIES PROGRAM COURSE PROPOSAL COVER FORM

Courses submitted to the GSC between 2/1 and 4/30 if approved, will be effective the following Spring.
Courses submitted between 5/1 and 1/31 if approved, will be effective the following Fall.

(SUBMISSION VIA ADOBE.PDF FILES IS PREFERRED)

DATE 12/20/2010

1. ACADEMIC UNIT: Physics Department

2. COURSE PROPOSED: PHY 334 Advanced Lab I 3
   (prefix)  (number)  (title)  (semester hours)

3. CONTACT PERSON: Name: Peter Bennett  Phone: 965-9523
   Mail Code: 1504  E-Mail: peter.bennett@asu.edu

4. ELIGIBILITY: New courses must be approved by the Tempe Campus Curriculum Subcommittee and must have a regular course number. For the rules governing approval of omnibus courses, contact the General Studies Program Office at 965-0739.

5. AREA(S) PROPOSED COURSE WILL SERVE. A single course may be proposed for more than one core or awareness area. A course may satisfy a core area requirement and more than one awareness area requirements concurrently, but may not satisfy requirements in two core areas simultaneously, even if approved for those areas. With departmental consent, an approved General Studies course may be counted toward both the General Studies requirement and the major program of study. (Please submit one designation per proposal)

   Core Areas                                      Awareness Areas
   Literacy and Critical Inquiry–L ☒               Global Awareness–G ☒
   Mathematical Studies–MA ☐  CS ☐               Historical Awareness–H ☐
   Humanities, Fine Arts and Design–HU ☐         Cultural Diversity in the United States–C ☐
   Social and Behavioral Sciences–SB ☐           Natural Sciences–SQ ☐  SG ☐

6. DOCUMENTATION REQUIRED.
   (1) Course Description
   (2) Course Syllabus
   (3) Criteria Checklist for the area
   (4) Table of Contents from the textbook used, if available

7. In the space provided below (or on a separate sheet), please also provide a description of how the course meets the specific criteria in the area for which the course is being proposed.

   CROSS-LISTED COURSES: ☒ No ☐ Yes; Please identify courses: ________________________________

   Is this a multisection course?: ☒ No ☐ Yes; Is it governed by a common syllabus? Yes

Rev. 1/94, 4/95, 7/98, 4/00, 1/02, 10/08
Chair/Director (Print or Type)          Chair/Director (Signature)
Date: _____________________________
Arizona State University Criteria Checklist for

LITERACY AND CRITICAL INQUIRY - [L]

Rationale and Objectives

**Literacy** is here defined broadly as communicative competence in written and oral discourse. **Critical inquiry** involves the gathering, interpretation, and evaluation of evidence. Any field of university study may require unique critical skills which have little to do with language in the usual sense (words), but the analysis of spoken and written evidence pervades university study and everyday life. Thus, the General Studies requirements assume that all undergraduates should develop the ability to reason critically and communicate using the medium of language.

The requirement in Literacy and Critical Inquiry presumes, first, that training in literacy and critical inquiry must be sustained beyond traditional First Year English in order to create a habitual skill in every student; and, second, that the skills become more expert, as well as more secure, as the student learns challenging subject matter. Thus, the Literacy and Critical Inquiry requirement stipulates two courses beyond First Year English.

Most lower-level [L] courses are devoted primarily to the further development of critical skills in reading, writing, listening, speaking, or analysis of discourse. Upper-division [L] courses generally are courses in a particular discipline into which writing and critical thinking have been fully integrated as means of learning the content and, in most cases, demonstrating that it has been learned.

Students must complete six credit hours from courses designated as [L], at least three credit hours of which must be chosen from approved upper-division courses, preferably in their major. Students must have completed ENG 101, 107, or 105 to take an [L] course.

Notes:

1. ENG 101, 107 or ENG 105 must be prerequisites
2. Honors theses, XXX 493 meet [L] requirements
3. The list of criteria that must be satisfied for designation as a Literacy and Critical Inquiry [L] course is presented on the following page. This list will help you determine whether the current version of your course meets all of these requirements. If you decide to apply, please attach a current syllabus, handouts, or other documentation that will provide sufficient information for the General Studies Council to make an informed decision regarding the status of your proposal.
Proposer: Please complete the following section and attach appropriate documentation.

### ASU - [L] CRITERIA

TO QUALIFY FOR [L] DESIGNATION, THE COURSE DESIGN MUST PLACE A MAJOR EMPHASIS ON COMPLETING CRITICAL DISCOURSE—AS EVIDENCED BY THE FOLLOWING CRITERIA:

<table>
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<th>YES</th>
<th>NO</th>
<th>Documentation Submitted</th>
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#### CRITERION 1: At least 50 percent of the grade in the course should depend upon writing, including prepared essays, speeches, or in-class essay examinations. Group projects are acceptable only if each student gathers, interprets, and evaluates evidence, and prepares a summary report.

1. Please describe the assignments that are considered in the computation of course grades--and indicate the proportion of the final grade that is determined by each assignment.

2. Also: Please circle, underline, or otherwise mark the information presented in the most recent course syllabus (or other material you have submitted) that verifies this description of the grading process—and label this information "C-1".

#### CRITERION 2: The composition tasks involve the gathering, interpretation, and evaluation of evidence.

1. Please describe the way(s) in which this criterion is addressed in the course design.

2. Also: Please circle, underline, or otherwise mark the information presented in the most recent course syllabus (or other material you have submitted) that verifies this description of the grading process—and label this information "C-2".

#### CRITERION 3: The syllabus should include a minimum of two substantial writing or speaking tasks, other than or in addition to in-class essay exams.

1. Please provide relatively detailed descriptions of two or more substantial writing or speaking tasks that are included in the course requirements.

2. Also: Please circle, underline, or otherwise mark the information presented in the most recent course syllabus (or other material you have submitted) that verifies this description of the grading process—and label this information "C-3".
**CRITERION 4:** These substantial writing or speaking assignments should be arranged so that the students will get timely feedback from the instructor on each assignment in time to help them do better on subsequent assignments. *Intervention at earlier stages in the writing process is especially welcomed*

**Identify Documentation Submitted**

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<th>YES</th>
<th>NO</th>
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1. Please describe the sequence of course assignments—and the nature of the feedback the current (or most recent) course instructor provides to help students do better on subsequent assignments.

2. **Also:**

   Please circle, underline, or otherwise mark the information presented in the most recent course syllabus (or other material you have submitted) that verifies this description of the grading process—and label this information "C-4".
<table>
<thead>
<tr>
<th>Criteria (from checksheet)</th>
<th>How course meets spirit (contextualize specific examples in next column)</th>
<th>Please provide detailed evidence of how course meets criteria (i.e., where in syllabus)</th>
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<tbody>
<tr>
<td>C1</td>
<td>The course grade is determined entirely by the lab reports</td>
<td>Pink highlight (C1)</td>
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<td>C2</td>
<td>Students set up equipment and take data</td>
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<td>C3 and C4</td>
<td>At least 4 separate reports are done in the semester.</td>
<td>Turquoise highlight (C3) and Green highlight (C4)</td>
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<td>Reports are returned with detailed comments before the next report is due.</td>
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PHY 334 Advanced Lab I
P. A. Bennett, Spring 2009

General Course Information

Course Objectives:
In this course, students will learn to:
1. Operate advanced laboratory equipment such as regulated, switching power supplies, multichannel analyzer, photomultiplier, pyrometer, digital multimeter, etc.
2. Maintain a research notebook with suitable organization and detail
3. Perform data analysis with commercial software (Excel, Kalaidagraph).
4. Write formal journal style reports, as detailed below.

Course Format:
Working in teams of 2 or 3, students perform measurements of "classic" physics phenomena, such as Compton Scattering, superconductivity, interference and diffraction, etc. Experiments are selected from a suite of available projects, according to the student ability and in consultation with the instructor. Typically, 4 projects will be done in a semester, using 2 weeks for set up and measurement, 1 week for analysis and 1 week for write-up. Each student turns in a formal written report for each experiment, in journal style, approximately 10 pages in length, with embedded figures, tables, equations and references (see below). The report must be sufficiently detailed, such that a skilled scientist could replicate the experiment. Papers are graded for content, format, and clarity, including proper spelling and grammar. The papers are graded and returned promptly, with a grading rubric and detailed comments to allow students to make improvements in their subsequent report(s). A sample report is given, as a guide.

Required Books:
1. Adrian C. Melissinos, Experiments in Modern Physics.
2. One full-size (8.5x11in) bound laboratory notebook. It should have ruled 8.5x11 sheets, numbered in the top corner. You will need this by the second week of the class.

Additional Books:
You also will need to read sections of the following books, which are available in the lab and also at Noble Library, on 2-hour reserve:
3. J.J. Brehm and W.J. Mullin, *Introduction to the Structure of Matter.* This contains useful information for both the X-Ray Physics and Compton experiments.

4. John R. Taylor, *An Introduction to Error Analysis*

5. Bevington and Robinson, *Data Reduction and Error Analysis.* All experimental physicists should own this standard reference book.

**Email:**
Important announcements, clarifications, etc will occasionally be sent to you by email, using your asurite email. Make sure that this address is functional and/or forwards to any other email address you use.

**Grading:**
The course grade is determined entirely by the lab reports. A numerical score is given for each report/experiment, based on evaluation of the report document as well as the lab notebook. These numerical scores are averaged to determine the course letter grade. Detailed descriptions of how to write good reports and how to maintain a good research notebook are given below. Each lab report is worth 25 points, for a total of 100 points. Late reports lose 2 points per day. Unexcused absences from classroom sessions lose 5 points per day. You must turn in all assigned reports (typically 4) to pass the course.

**Computing:**
There are 7 PCs available in the lab running WinXP. Login using your asurite ID on the ASUAD domain. They are fully locked down, so no user files or preferences are saved upon logoff. You need to copy data to flashdrive or your asurite folder at the end of each session. Standard software is available including Office2003, Graphical Analysis (Vernier), Kalaidagraph, Firefox and many others. You can print to the "Advlab" printer, but please do this for data only, as needed in class. Longer items (such as handouts) should be printed elsewhere.
Experiment Handouts:

All handouts for the experiments are available as downloads from the table below. These are updated occasionally, so be sure to note the date on the footer of each page.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date Posted</th>
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<tbody>
<tr>
<td>Thermionic Emission.pdf</td>
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<tr>
<td>TeachSpinHelp.pdf</td>
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<tr>
<td>Magnetic Moment.pdf</td>
<td>3-17-09</td>
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<tr>
<td>Compton Scattering.pdf</td>
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<td>X-ray Emission.pdf</td>
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<tr>
<td>Electronics</td>
<td>In Progress</td>
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<tr>
<td>Electron Diffraction</td>
<td>In Progress</td>
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</table>

Additional Syllabus Materials

Data fitting assignment: FitsAssign.pdf

Sample grading rubric: GradingRubric.pdf

Instructions for writing the formal lab report: LabReports.pdf

Mechanical Behavior of a Spring, R. Hooke, DePotentia Restitutiva (1678): SampleLabReport.pdf

How to maintain the lab notebook: LabNotebook.pdf

Reference handouts for data analysis:

Data Analysis General.pdf (18pp)
DataFits.pdf (7pp)
LogLogPlots.pdf
Graphical Analysis Tutorial.pdf
**Academic Integrity:**

Students are responsible for reading and following ASU policies on academic integrity, available at http://provost.asu.edu/academicintegrity. In this course, students will collaborate in small teams to set up equipment and collect data. They are encouraged to collaborate also in the analysis, and may share data and charts, but the collaboration should be cited in the form of co-authors. Students are expected, however, to produce individual written reports to present, interpret and discuss their results.

**Disabilities:**

ASU offers support services for students with disabilities, as detailed at www.asu.edu/lrc and http://www.asu.edu/studentaffairs/ed/drc/.
## Grading Rubric for Lab Reports

<table>
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<tr>
<th>Experiment:</th>
<th>Person:</th>
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<td>Plots</td>
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<td>Score (5pt)</td>
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### Content

| Procedure | | Data | | Fits | Error Disc | English | Narrative | Interp | | Score | 15 |

### Notebook

| Index | | Dates | | Figs | Narrative | Tables | | Score | 5 |

Late/Absent

Total 25
Lab Reports for PHY334 (Advanced Lab)
P. Bennett

Introduction
It is absolutely critical for researchers at all professional levels (student, professor, industrial technician, scientist, etc) to be able to communicate their activities effectively. Indeed, this is a life-skill that extends beyond physics lab courses and impacts your ability to get and maintain a job as well as your personal satisfaction in working with colleagues in any context. In this class we deal with written presentation. Hopefully, you will receive guidance in oral presentation elsewhere. Written reports can take many forms, such as a progress report, sales pitch, informational article, research paper, etc. These all involve the same core principles. Here we will utilize a format that blends research paper and progress report.

A well-written report conveys the essence of an experiment in complete but concise terms. It should be written with proper English and good formatting using sound protocol for figures, units, errors, etc. It should have structured redundancy such that an experienced reader (like the lab instructor) can navigate it easily, at increasing level of detail, by examining in order: title, abstract, figures & tables (with captions) and lastly, narrative. A professional reader will exploit this hierarchy while doing a literature search, to pull out a few key papers, figures, numbers or sentences from hundreds of publications in a matter of a few hours.

Basic Outline
Your lab report should resemble a professional publication, adapted slightly for the classroom setting. A sample lab report is available on the web page, and should be studied carefully. The basic sections of your report should be:

Cover page: Title, abstract (see below), your name, partner name(s), date.
Introduction: State the purpose, background and theory. Briefly explain the physical basis for the experiment. Simple theory should be derived – complex theory can be moved to the appendix or just cited by reference.
Procedure: Give enough information that a skilled person could repeat the experiment. Describe any subtle procedures, such as “care was taken to align...”. Avoid excessive detail or banal statements, like “first we this, then we that”.
Results: Build a discussion of results around figures and tables that are embedded into the document (see format details below) with numbered captions (Fig. 1 etc). The text should be on the same page as the graphic. Often, you will determine a physical value from the slope and intercept of a linearized plot. State this directly, as “…we determined a spring constant $k_d = 1.51 \pm 0.03 \text{ N/m}$ and effective mass $m_0 = 110 \pm 20 \text{ g}$.” Explain the calculations, perhaps in an appendix if lengthy.
Discussion: This section is for interpretation or comparison of your results. This should include detailed discussion of uncertainties.
Conclusion: Summarize your main results, giving value, uncertainty and units. This can be a small summary table or a single sentence, as appropriate.
Appendices: Reserved for lengthy calculations (can be done by hand), multiple plots or tables that “don’t fit” in the main body, etc. Do not attach large amounts of raw data.
Abstract:
The abstract deserves special mention. It is a line-item in the grading rubric and should be written very carefully. It should state what you did, how it was done, and the main result, all in concise terms. 3 or 4 well-chosen sentences will usually suffice. Whenever possible, state numerical results and include units and uncertainty. Do not include introductory or procedural material, such as “The force between charges is called the Coulomb force.” or “We looked at this and that....and found good agreement with the theory”

Length and style
The total narrative should be about 1000-2000 words. Anything longer likely has irrelevant detail or redundant segments. A good procedure for writing is to first make good figures, do all calculations, write phrases (not complete sentences) to denote the key points, then finally make complete sentences. A lot of unprofessional writing can be compressed by a factor of 2 with negligible loss of content. Try compressing your own writing, after leaving it sit for a day or so. A short, accurate report is much better than a long, rambling one.

Word Processing Tips
1. Keep figures and tables separate from the narrative while writing, and embed them only when the text is essentially done. Make them the full page width, and with font large enough for easy reading.
2. Learn the tables feature in WORD, with its various formatting items (spacing, bold, insert, delete, borders, etc). Excel data are best formatted by copy/paste into a word table.
3. Use white space and bold or italics to separate major items.
4. Set up “hot keys” for Greek letters, (±) symbol, super/sub scripts, etc.
5. Write equations using MathType or the like, leave blank lines above/below each equation, and number them in the right margin for reference. Long or numerous equations can be done by hand and attached or patched in.

Units
On September 30, 1999, the Mars Climate Orbiter accidentally plunged into the Martian atmosphere and was vaporized, costing NASA (and public taxpayers) $125 million. This happened because two engineering teams mixed metric vs. English units for rocket thrust, and radioed the wrong numbers to the obedient spacecraft. This major embarrassment provides a real life enduring lesson for beginning scientists and engineers everywhere: Any time you write a physical quantity in your report (and the notebook!), you must include units! Failure to do so will cost you grade points now, but we hope will prevent the loss of spacecraft, automobiles and airplanes in the future.

Significant Digits
Pay attention to significant digits everywhere. Anything more than 3 digits is seldom justified. This should reflect the inherent uncertainty of the measurement (known or anticipated). For example, a digital meter may show 4 or 5 digits, but your experiment will almost certainly not be that good, so you should record 3 digits at most. Writing 5 digit values into your notebook and,
worse, into your report is not “more accurate” – but instead is a sign of naïveté. It is unprofessional, misleading and a waste of ink, paper and effort.

Data Tables
Put results into tables whenever possible - generally for anything more than 2 quantities. All tables should be properly formatted with labels, units, uncertainties and a short numbered caption such as “Table I. Resistance vs distance”

Plots
A good plot conveys a lot of information, in an accessible way. An example is shown in the sample report. Guidelines for making a good plot:
1. Use the full page width. Legends and title and even axis labels can be put inside the box to make more space for the data.
2. Label both axes, and include units
3. Use a caption such as “Figure 1. Distance vs time for blah blah”
4. Use large fonts everywhere.
5. Use sensible values (generally integer ticks) on both axes, such that a feeble-minded professor can interpolate readily.
6. Use large data points (markers).
7. All plots should include error bars on the data points.
8. Never “connect the dots”. Occasionally, it is useful to show a “guide to the eye”, which should be clearly noted and should be smooth, not jagged.
9. Show theory with a line (not points), to distinguish it from data (points).
10. In EXCEL, the appropriate chart type is usually "XY-scatter".

Data fits
Data fits and analysis are discussed in detail in the reference notes on the web page. Here, we simply note that, in most cases you should linearize the plot to obtain a straight line fit, then obtain values for slope and intercept and uncertainties for each. This is nicely handled with Graphical Analysis or Kalaidagraph, which are both available in the lab and also at computing sites around campus. This can also be done with Excel, but is very clumsy. Algebraic manipulation is often required to convert slope and intercept into physical parameters of interest and error propagation often is required to find the uncertainty in the values.

Uncertainties and Errors
The terms “error” and “uncertainty” are profoundly different. The term “error” refers to the difference between a measured value and a theory value, while “uncertainty” refers to the variance obtained from repeated measurements of some parameter. A measurement can only validate a model (theory) if it agrees with the model prediction within the measurement uncertainties. That is, if the error is smaller than the uncertainties. Experimental results are virtually useless if the associated uncertainties are not known. Quantification of errors is a trivial (generally useless) exercise – just tabulate the difference between theory and data for all measurements. Quantification of uncertainties is a profound concept, but can be subtle, elusive,
or even obscure in practice. In the classroom environment, the uncertainties in a measurement are more important than the value itself. In this sense, we don’t mind using “crummy equipment”, because it makes the uncertainties more obvious. Our goal is to learn how to quantify uncertainties, identify their source, and minimize their size by good technique.

The procedures for handling experimental uncertainties are given in detail in the reference handouts. Here we only discuss how to present uncertainties in your report. A common faux pas of students is to list out everything they can think of that “went wrong”, using vague qualitative terms, such as “the meters were noisy”, “the beam was fuzzy”, and of course the classic “...there was a lot of human error...”. Such statements prominently reveal that the student has learned nothing at all from this course. Instead, you should try to identify specific uncertainties, and suggest how to minimize them. Systematic uncertainties are especially important, since they point the way to improvements of method, inadequacy of theory, or even (rarely) new physics! For systematic errors, you should consider whether your hypothesis “goes the right direction” for the error, that is, it should have the effect of bringing your experiment and theory closer together.
Mechanical Behavior of a Spring
R. Hooke, DePotentia Restitutiva (1678)

We have measured the strength “k” of a mechanical spring using both static and dynamic methods. Masses are hung from a vertically suspended spring and the stretch length and oscillation period are measured. For the static method, we obtained $k_s = 1.45 \pm 0.05 \text{ N/m}$, while for the dynamic method, we obtained $k_d = 1.51 \pm 0.03 \text{ N/m}$. These measurements agree within their uncertainty, but the dynamic method is more precise. The static method also revealed a built-in tension, such that the “rest length” $L_0 \sim 10\text{cm}$ is less than the minimum physical length $L_m=12\text{cm}$. The dynamic method revealed that the mass of the spring itself affects the oscillation period via an effective mass of $m_0 = 110 \pm 20 \text{ g}$.

Introduction

In this lab the mechanical behavior of a spring is investigated. Springs are characterized by a linear restoring force and exhibit simple harmonic motion. This behavior occurs in many other physical systems, such as 3D solids, waves, electrical circuits, etc. The concept is central to many subjects, and is discussed at length in physics, electrical engineering and mechanical engineering textbooks. Here we will measure the force constant using both static and dynamic methods and compare with Hooke’s law.

Theory

An ideal spring follows a linear force-distance relation and is massless. The static behavior then is described by:

$$F(X) = -k_s (X-X_0) \quad \text{Eq. 1}$$

where $F$ is the force exerted by the spring (opposing the external stretch force), $(X-X_0)$ is the stretch distance, measured from the resting position $X_0$ where the force is zero, and $k_s$ is the static spring constant. In this lab, the force is generated by calibrated weights hung on a vertically suspended spring. Any system described by Hooke’s law will exhibit “simple harmonic motion" if it is displaced from $X_0$ and released. The system will oscillate at a frequency given by

$$\omega^2 = k_d/m \quad \text{Eq. 2}$$

where $\omega$ is the angular frequency and $k_d$ is a dynamic spring constant. For perfect systems, we expect $k_d = k_s$. Real springs have a non-zero mass, but still exhibit a single oscillation frequency, given by

$$\omega^2 = k_d/(m+m_0) \quad \text{Eq. 3}$$
where "m" is the applied mass and \( m_0 \) is an effective mass. It can be shown by Lagrangian method, that \( m_0 \) is 1/3 of the physical spring mass (Analytic Mechanics, Fowles and Cassiday).

**Procedure**

For the static measurements, calibrated weights were hung from the spring and the overall length between the centers of the two end-hooks was measured using a meter stick, by sighting carefully to minimize parallax. Data are taken first by adding and then by removing weights to establish uncertainties.

For the dynamic measurements, the elapsed time for 3 complete cycles of oscillation was recorded for each mass. Both the start and stop times were marked at the top of the oscillation, after “synchronizing” to the pace of the motion. The amplitude was kept below 3 cm, to avoid non-linearity. A small decay of amplitude after 3 beats was noticed, but is not expected to affect the average period.

**Results**

![Graph showing the data for the static measurement. The circles are for adding weights, the squares for subtracting weights.](image)

Fig. 1 Spring length vs applied mass. The circles are for adding weights, the squares for subtracting weights.

Figure 1 shows the data for the static measurement, which are tabulated in the appendix as Table A1. The “adding” and “subtracting” data agree within ± 0.5 cm, which establishes the random uncertainties. The data show a linear trend, with no systematic
deviation, except for applied mass below $m = 0.4\text{kg}$ where the length is constant because the coils are touching. This region is excluded from the analysis (see below). The remaining data are fit to equation 1, using plot variables $L = (x-x_0)$ and $F = mg$. Thus, the fit line is $L(m) = -\frac{g}{k}m$, with slope $S = 6.75 \pm 0.24 \text{ cm/kg}$, and intercept $I = 9.8 \pm 0.24 \text{ cm}$. This yields a static spring constant $k_s = 1.45 \pm 0.05 \text{ N/m}$. Calculations are shown in the appendix.

![Mass-Spring Oscillator](image)

**Figure 2. Linearized plot of oscillation period vs mass.**

Figure 2 shows the dynamic behavior, which is tabulated in the appendix, Table A2. These data are fit with a linearized plot to equation 3, using plot variable $T^2$, where $T^2 = \left(\frac{2\pi}{\omega}\right)^2 = \left(\frac{2\pi}{\omega}\right)^2 \frac{k}{m+m_0}$. The fit region is limited to $m > 0.4\text{kg}$, as for the static data. The fit line yields slope $S = 26.1 \pm 0.5 \text{ sec}^2/\text{kg}$ and intercept $I = 2.84 \pm 0.5 \text{ sec}^2$, corresponding to a dynamic spring constant $k_d = 1.51 \pm 0.03 \text{ N/m}$ and effective mass $m_0 = 110 \pm 20 \text{ g}$. Calculations are shown in the appendix.

**Discussion**

For the static measurement, the fit to Equation 1 is good. That is, there is no systematic deviation from the trend. All physical systems that follow this behavior shall henceforth be said to follow Hooke’s Law. We note that, for applied mass less than 0.4kg, the spring has a fixed length of 12 cm. This can be understood as a pre-loaded tension, corresponding to a “rest length” of $L_0 = 10.2 \pm 0.14 \text{ cm}$ which is shorter than the physical length of $L_m = 12 \text{ cm}$. The scatter in the data (random uncertainty) is about $\pm 0.5\text{cm}$. This is attributed to parallax errors in reading the length. This could be improved using a travelling microscope, or more simply with a mirror assembly next to the ruler to allow auto-collimation of the sighting. It was expected that the stretch length might drop below the trendline for large applied force, due to material limitations (real springs get stronger), but this was not observed. This behavior might become visible with reduced scatter.
For the dynamic measurement, the fit to Equation 3 is good, meaning there is no systematic deviation from the trend, within the scatter of approximately 0.7 sec. Concerning this scatter: Some uncertainty is expected due to errors of start and stop times, but these are minimized by “synching” to the motion before timing, and are estimated to be ~ 0.3 sec. This could be improved, in any case, using a photo-gate. We suspect that the scatter mainly arises from variation in the amplitude of the motion, either due to variable starting displacement or due to a variable waiting time before the start of timing. This could be improved by more diligent procedure.

The results for the static vs dynamic method are shown in Table 1. We find that these two methods agree within their uncertainties. The dynamic method is more precise.

<table>
<thead>
<tr>
<th>Method</th>
<th>Value for k (N/m)</th>
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</thead>
<tbody>
<tr>
<td>Static</td>
<td>1.45 ± 0.05</td>
</tr>
<tr>
<td>Dynamic</td>
<td>1.51 ± 0.03</td>
</tr>
</tbody>
</table>

Table 1. Comparison of static vs dynamic results for spring constant.
### Appendix

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Length (cm) increasing</th>
<th>Length (cm) decreasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>0.20</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>0.30</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>0.40</td>
<td>12.8</td>
<td>12.5</td>
</tr>
<tr>
<td>0.50</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>0.60</td>
<td>13.9</td>
<td>14.0</td>
</tr>
<tr>
<td>0.70</td>
<td>14.8</td>
<td>14.4</td>
</tr>
<tr>
<td>0.80</td>
<td>15.1</td>
<td>15.2</td>
</tr>
<tr>
<td>0.90</td>
<td>16.1</td>
<td>15.9</td>
</tr>
<tr>
<td>1.00</td>
<td>16.4</td>
<td>16.4</td>
</tr>
<tr>
<td>1.10</td>
<td>17.4</td>
<td>17.1</td>
</tr>
<tr>
<td>1.20</td>
<td>17.9</td>
<td>18.0</td>
</tr>
<tr>
<td>1.30</td>
<td>18.7</td>
<td>18.5</td>
</tr>
<tr>
<td>1.40</td>
<td>19.0</td>
<td>19.1</td>
</tr>
<tr>
<td>1.50</td>
<td>19.6</td>
<td>19.9</td>
</tr>
</tbody>
</table>

Table A1. Length of spring for various applied masses.

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>3*T (sec)</th>
<th>T² (sec²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.20</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.40</td>
<td>11.2</td>
<td>14.0</td>
</tr>
<tr>
<td>0.50</td>
<td>12.2</td>
<td>16.5</td>
</tr>
<tr>
<td>0.60</td>
<td>12.7</td>
<td>18.1</td>
</tr>
<tr>
<td>0.70</td>
<td>13.6</td>
<td>20.4</td>
</tr>
<tr>
<td>0.80</td>
<td>14.6</td>
<td>23.8</td>
</tr>
<tr>
<td>0.90</td>
<td>15.3</td>
<td>25.9</td>
</tr>
<tr>
<td>1.00</td>
<td>16.0</td>
<td>28.3</td>
</tr>
<tr>
<td>1.10</td>
<td>16.8</td>
<td>31.4</td>
</tr>
<tr>
<td>1.20</td>
<td>17.7</td>
<td>34.7</td>
</tr>
<tr>
<td>1.30</td>
<td>18.1</td>
<td>36.3</td>
</tr>
<tr>
<td>1.40</td>
<td>18.9</td>
<td>39.7</td>
</tr>
<tr>
<td>1.50</td>
<td>19.5</td>
<td>42.5</td>
</tr>
</tbody>
</table>

Table A2. Oscillation period vs applied mass.
Derivation of spring constant values

**Static**

\[ F(x) = -k(x-x_0) \]

\[ p_0 + L(m) = (x-x_0) = \frac{-F}{k} = \frac{-mg}{k} = \frac{-9}{k} \, \text{m} \]

slope \( S = \frac{-9}{k} = 6.75 \pm 0.24 \, \text{cm/kg} \)

\[ k = \frac{98.0}{6.75} = 14.5 \, \text{m/kg} \]

Note: \( 1 \text{m/kg} = 1 \text{N/m} \)

since both MKS.

\[ \frac{\Delta S}{S} = -1 \cdot \frac{\Delta k}{k} \] (Power law rule)

\[ \Delta k = \frac{\Delta S}{S} \cdot k = 0.05 \] So \( k_5 = 1.45 \pm 0.05 \text{N/m} \)

**Dynamic**

\[ \omega^2(m) = \frac{k(m+m_0)}{I} \]

\[ T^2(m) = \frac{(\omega)^2(k(m+m_0))}{k(m+m_0)} \]

slope \( S = \frac{4\pi^2}{k} = 26.1 \pm 0.5 \text{sec}^2/\text{kg} \); \( k = 1.51 \text{ kg/sec}^2 \)

\[ \Delta k = \frac{\Delta S}{S} \cdot k = 0.029 \] So \( k_d = 1.51 \pm 0.03 \text{ N/m} \)

\[ I = S \cdot m_0 = 2.84 \pm 0.5 \text{ sec}^2 \]; \( m_0 = \frac{I}{S} = \frac{2.84}{26.1} = 0.109 \text{ kg} \)

\[ \Delta m_0 = \frac{\Delta I}{I} \cdot m_0 = 0.19 \] So \( m_0 = 110 \pm 20 \text{ g} \)