Precision Roller Experiment for Intermediate Laboratory

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Here is the intro that I provide the students:

Physics 2151W Design Project

Precision Roller

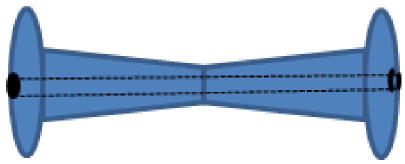
This is to be a design project in which you plan, develop and create a two-wheeled axle that will roll smoothly down an inclined plane with a predictable "time-of-flight", to use particle physics lingo---a "time-of flight" that you will measure using equipment from the introductory lab. The inclined plane will be about a half meter wide and will be a bit more than a meter in length, with a "pitch" of about 1:12 or 2:12, to use roofing lingo.

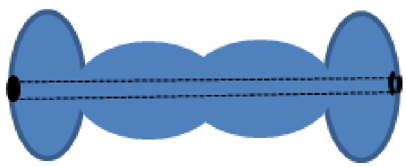
Some rules:

The bulk of the roller is to be machined from aluminum and PVC in three pieces: two wheels, each no more than 4 inches in diameter and a "fancy" axle no more than a foot long.

What's "fancy" about the axle, you ask?

1) The axle must have a hole along its symmetry axis so that a steel rod of diameter between ½ in and 1 inch can be inserted and secured with one or more set screws; thus your roller will have two travel modes (and two "times-of flight"): (A) without steel rod and (B) with steel rod. One goal is to be able to theoretically predict these travel times before doing the rolling experiment as accurately as possible.
2) The silhouette (profile) of your roller between the wheels must include a non-trivial functional form, anything from piecewise linear (but not merely a constant) to bedpost-complicated...be creative, even artistic, but you'll want to be able to describe it (and the wheels) with a friendly mathematical function so that you can correctly compute its moment of inertia and center-of-mass, so that you can accurately predict its time-of-flight. In addition to computing the moment of inertia about the axis of your roller, you will be expected to remove one wheel from your roller and compute the center of mass of the remaining solid, and compare the theoretical value to the measured location of its center-of-mass, so choose your function with that in mind.



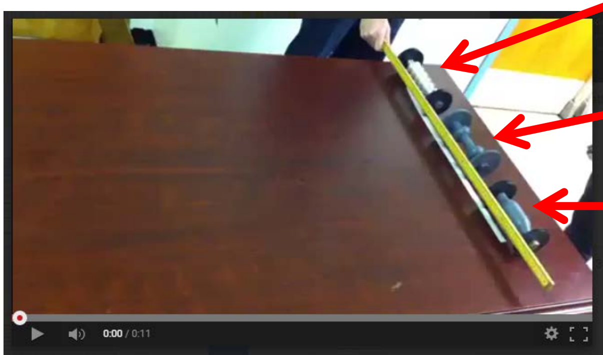


---[Gary White, GWU Physics Intermediate Lab, Fall 2015]

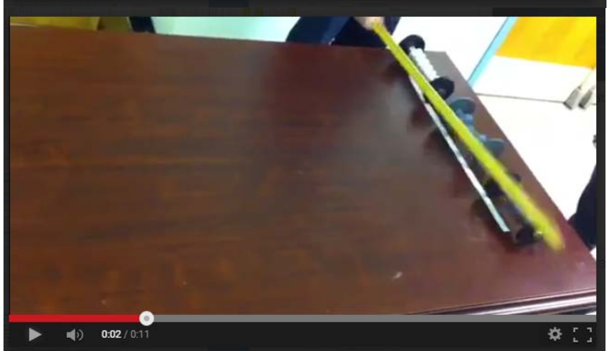
Some of the “fancy rollers” that students in Phys2151W made in the machine shop:

The first round of data-taking was qualitative. Which of these rollers do you think should win a race down an inclined plane?

(Spoiler alert: the next page shows a race between roller A, B and C, so make your predictions before turning the page…)



Which do you think will win, Roller A, B, or C?



Note that Roller B gets hung on the starting tape…

Roller C wins by about a wheel diameter…note that it has more of its relative mass near its axis of rotation (because the axle is made of aluminum rather than plastic)

Equipment list:

1) Machine shop access, training, tools for students so they can craft their rollers
2) Otherwise, equipment needed is minimal---
    a. stop watches, and rulers and an inclined plane for initial measurements---
    b. some students used motion detectors and computer software for time of flight---
    c. other students used video analysis with Tracker
    d. one student used an Arduino and pressure sensitive strips to get even more precise timing for his final project (see attached results below).

Here is the "write a letter to your high school physics teacher" assignment

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Your writing assignment for your precision roller experiment is to write a long letter/story to your high school physics teacher (or some other approved physics-knowledgeable person from your past) about your experiences and findings regarding your precision roller experiment including the following ingredients:

1) Describe in your own words the *a priori* goals of the precision roller project that I specified, as well as any personal goals that you might have had for the project, and how well they meshed, if appropriate.
2) Describe how you went about determining the shape and composition of your roller. Why did you choose the functions and materials you chose? What compromises did you have to make?
3) Describe a moment when you had to concentrate really intensely during the actual construction of your roller. What worried you, and how did you resolve any problems that arose?
4) Looking back on the project, discuss whether you feel like your effort was successful in terms of the original goals of the project, or in other ways that weren't part of the original goals.
5) Identify and comment about any aspects of mathematics, or of physics, or of experimental science in general, that you think you understand better now because of this project.
6) Indicate and discuss at least one aspect of the project that connects in some way to the reader to whom the letter is addressed, based on your mutual history.
7) Looking back, what surprised you most about the project?
8) In addition you should include the following:

Describe both methods (starting from conservation of energy and then starting from the torque equation) for getting the formula for the "time of flight"…you can put these derivations in an appendix if it doesn't fit in the flow of your letter well, but you should give the formula in your letter proper and comment on how it makes sense in a way that the reader can see some of the features of the formula that you have learned to appreciate.	Explain a bit about getting estimates for all the quantities needed for your theoretical time of flight formula and their associated uncertainties…what was the largest source of uncertainty in determining the theoretical time of flight, in your view? Can you explain qualitatively to your reader why this was the largest source?	Explain a bit about getting your experimental time of flight formula and its associated uncertainties…what did you conclude was the best way to measure the experimental time of flight? What evidence would you cite for your reader to support your conclusion?

You are to turn in two copies of this letter, along with an appropriately addressed and stamped envelope on April 12 in the morning classtime.

Here are some data and student notes from the experiment:

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* continued from p.37

$$a = \frac{mg\sin\theta}{\frac{I}{r^2} + m} \; ; \quad V_f = \frac{mg\sin\theta}{\frac{I}{r^2} + m} t \; ; \quad V_0 = 0 \; ; \quad d = L$$

$$V_f^2 = V_0^2 + 2ad$$

$$\left(\frac{mg\sin\theta}{\frac{I}{r^2} + m}\right)^2 t^2 = 2\left(\frac{mg\sin\theta}{\frac{I}{r^2} + m}\right) L$$

$$t^2 = \frac{2L}{\left(\frac{mg\sin\theta}{\frac{I}{r^2} + m}\right)}$$

$$t^2 = \frac{2L\left(\frac{I}{r^2} + m\right)}{mg\sin\theta}$$

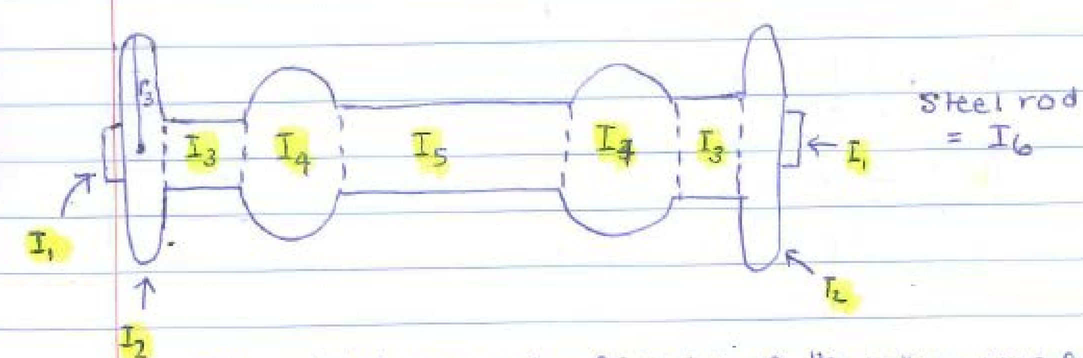
$$t = \sqrt{\frac{2L\left(\frac{I}{r^2} + m\right)}{mg\sin\theta}}$$

$$t = \sqrt{\frac{2L\left(\frac{I}{Mr^2} + 1\right)}{g\sin\theta}}$$

some student notes about Roller A

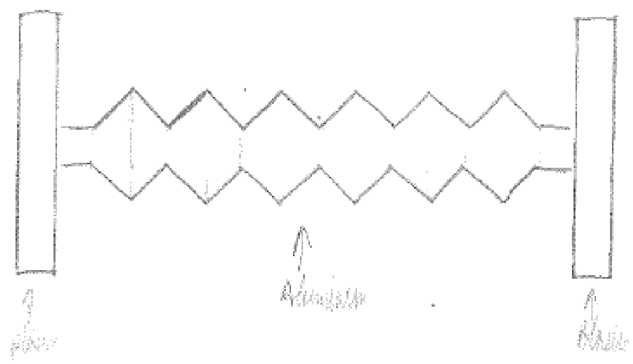
Variables:
- L = length of ramp
- M = mass of roller
- I = moment of inertia of roller
- R = radius
- g = accel. due to gravity (9.8 m/s²)
- θ = angle of inclined plane

Calculation of Moment of Inertia of Roller

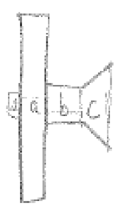


The total moment of inertia of the roller was found by determining the individual moment of inertias of the different some more student notes about Roller C

The shape I chose is as follows

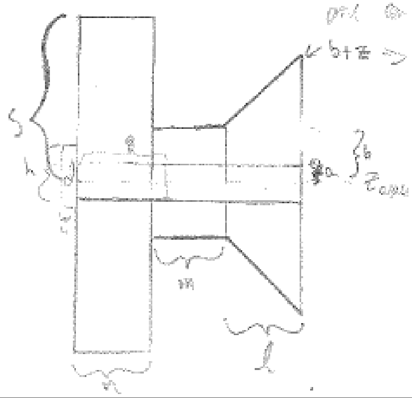


In order to calculate the moment of inertia all one has to do is calculate three main pieces of the roller (see below)



The roller has two wheels (a), two straight axle segments (b) and 12 angular segments (c).

Thus the moment of inertia, I, will be $2I_a + 2I_b + 12I_c$ when there is no steel axle placed inside. When the steel bar is inside one can simply add I_{steel} to the calculation



$$I_a = \rho_a \int_0^{2\pi}\int_0^{h}\int_a^{s} r^2\, r\,dr\,dz\,d\theta$$

$$I_b = \rho_b \int_0^{2\pi}\int_0^{m}\int_a^{b} r^2\, r\,dr\,dz\,d\theta$$

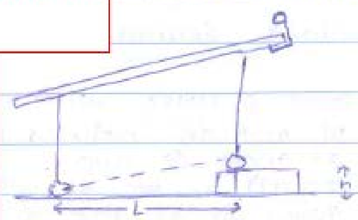
$$\rho_b = \rho_c = \rho_{Al}$$

$$I_c = \rho_c \int_0^{2\pi}\int_0^{l}\int_a^{b+z} r^2\, r\,dr\,dz\,d\theta$$

+I bolt calculations to follow.

First we predicted winners and "raced" the rollers to hone our qualitative intuition about rollers; next we began quantitative experiments involving stopwatch and meterstick data

Precision: Rollers Experiment



Day-of Experiment:
① We adjusted the height of the table using boxes to calculate the angle θ. We attempted to get this angle as close to 4° as possible
② we attached the motion sensor at the edge of the table, which would give us x(t), v(t) and a(t) graphs
③ we marked 1.5m from the end of the table as our starting point

Measurement of Angle θ

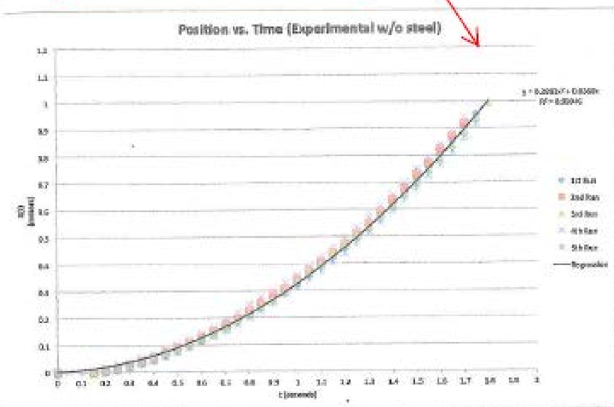
	L	h			
Sci	100.0	7.2	θ =	4.12°	low 4.08°
Oliver	100.9	7.8	θ =	4.42°	high 4.86°
Gregg	100.5	8.5	θ =	4.83°	
			θ_{avg}	4.46°	$\sigma_{\bar{x}}$ = 0.17°

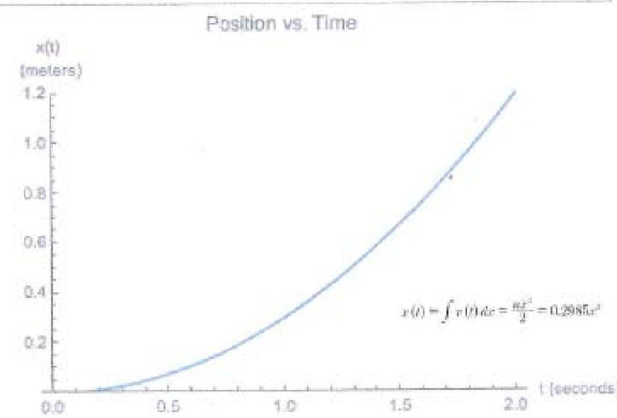
Stopwatch Data

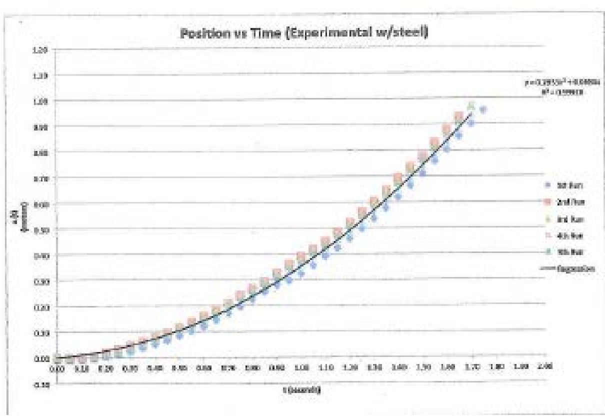
Measurer: Roller	Sci	Oliver		Avg for each trial	Value ± Uncertainty
	2.26	2.44	Roller E (average time)	2.35	2.36 ± 0.03s
	2.24	2.36		2.30	
	2.46	2.38		2.42	
	2.38	2.46	Roller F (average time)	2.42	2.32 ± 0.04s
	2.32	2.20		2.26	
	2.32	2.23		2.28	
	2.30	2.32	Roller A (average time)	2.31	2.28 ± 0.01s
	2.27	2.29		2.28	
	2.30	2.21		2.26	
	2.23	2.35	Roller F with central steel rod (average time)	2.29	2.26 ± 0.02s
	2.30	2.26		~~2.28~~ ~~2.31~~	
	2.23	2.18		2.21	

Go!Motion detectors from Vernier and Logger Pro were used for second round of data-taking

Roller C

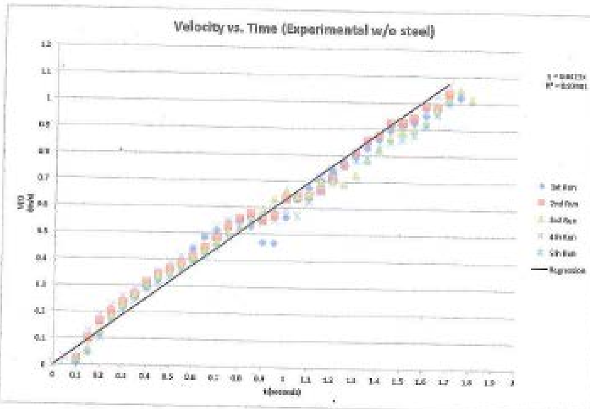


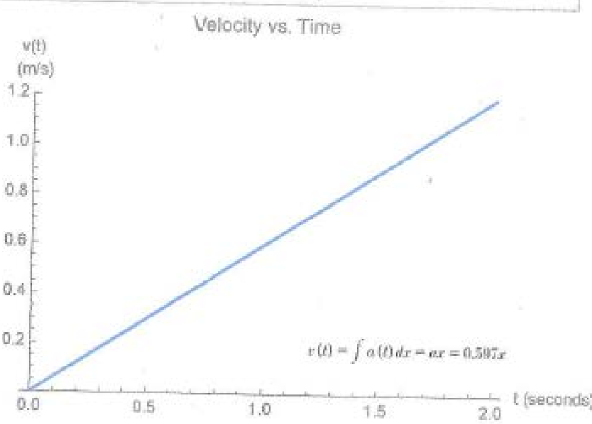


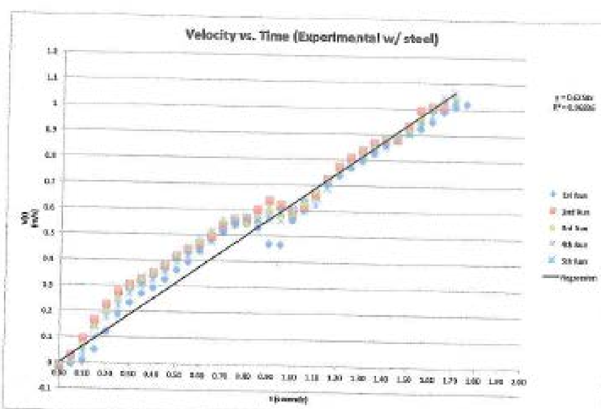


The position v. time graphs are very close to the theoretical graph. At the max x value on the graph (x=2) the largest discrepancy should be present as the value is squared. All values are w/in 0.1 second of one another from both exp. graphs and the theoretical. This gives credibility to the theoretical.

Some reasons for differences may include, how slick the table was, anomalies in the table, and "assists" during release. This assist may have been due to a change in air pressure "pulling" the roller forward or affecting the sonar sensor.







The velocity v. time graphs are much more interesting. Between approx 0.8 and 0.9 s, there is clearly an anomaly in the data. This is likely the fault of the table.

If it were the roller one would expect the anomaly to change between runs as the wheel is not in the same starting position each time. As the anomaly shows up at relatively the same place each time it is likely a fault present on the table. A slick spot on the table would cause an increase in velocity as all energy icarus for that period would go to translational movement as opposed to rotational. So it is likely not a slick spot. It is probably a sticky spot or a bumpy spot

Here are some of the impressions of the lab from one student:

A very interesting fact right off the bat is that the acceleration of the roller after the steel was inserted was the fastest. All of the average times for the [illegible] were for the roller after the steel inserted [illegible] somewhat of a [illegible] as to why this is. One would think a heavier roller would [illegible] but this was not the case (in theory or practice).

Conclusion

All in all, I am very happy w/ the results of this lab. Whenever your prediction matches experiment, it feels good, but having crafted something [illegible]

wrong one.

All in all, I am very happy w/ the results of this lab. Whenever your prediction matches experiment it feels good, but having crafted something and predicted correctly is a double win. The margin of error calculation...While this experiment was enjoyable I would like more accurate measurements. Perhaps a ramp w/ sensors built-in for start and stop? Either way this experiment has dramatically improved my intuition for MoI [moment of inertia].

This student took it one step further and crafted an Arduino timer with pressure sensitive starting and finish lines…here's some of his data.

more Roller C data

	High (3rd step)			
	Arduino (theta)	22.35	Trig (theta)	23.1±.4
	Times (s) ±0.05 s			
Run	Hoop	Cylinder	Roller w/o steel	Roller w/Steel
1	1.29	1.16	0.99	0.95
2	1.30	1.16	0.98	0.98
3	1.29	1.20	0.99	0.99
4	1.31	1.14	1.00	0.97
5	1.31	1.13	1.02	0.98
6	1.31	1.16	0.96	0.98
7	1.29	1.15	0.98	0.99
8	1.29	1.14	0.97	0.97
9	1.29	1.13	0.96	0.99
10	1.28	1.13	1.10	0.99
Average	1.30	1.15	1.00	0.98
Std Dev	0.01	0.02	0.02	0.01

Time of flight for hoop (theoretical) = 1.34 +/- .03 s

Time of flight for solid cylinder (theoretical) = 1.16 +/- .03 s

Time of flight for Roller C (theoretical) = 0.95 +/- .05 s

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The precision experiment above is one of about 6 during the semester, plus a final project. The other experiments for the course are given below in the course syllabus.

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Physics 2151W Spring 2014---R 9:30-10:20 in Cor 209 and 10:30-2pm Cor 212A (CRN 84235 and 83689)

Welcome to 2151W Intermediate Laboratory I: Techniques and Methods: (3 credit hours) Experiments in electromagnetism, classical and quantum mechanics, atomic and nuclear physics with emphasis on experimental methods. Prerequisite. Phys 1021. Laboratory fee.

Required Texts and equipment:

1) Hughes and Hase, Measurements and their Uncertainties, (2010) ISBN: 978-0-19-956633-4, available in bookstore
2) Strakovsky, Intermediate Laboratory I: Techniques and Methods, available for $15 from departmental secretary in Corcoran 105

Instructors: Gary White, Corcoran 104F, 202-994-8288, gwhite@gwu.edu; with Laura Lai, llai@gwmail.gwu.edu

Office Hours: Tuesday 9:30-11 and 1-3, Thursday from 2-3 and Friday from 9:30 to 10:30, and by appointment

Much of the structure of this class is taken from a previous version of the class taught by Igor Strakovsky and from a similar class taught by Tim Gfroerer at Davidson College, for which and to whom I am very grateful.

Objectives: The successful student will obtain:

- Practical experience with modern laboratory instrumentation including error analysis, machine shop skills, and data acquisition.
- Experimental familiarity with a variety of electromagnetic, classical, quantum mechanical, atomic and nuclear physics systems.
- Practice with literature searches and finding/using appropriate theoretical resources.
- The discipline necessary to record daily progress and maintain a detailed laboratory notebook.
- The computational skills required to perform advanced data analysis and mathematical modeling of experimental results.
- Proficiency in writing a formal laboratory report.
- Practice in oral communication and presentation of research results.
- Appreciation of, and ability to expound upon, physics as an exemplar of how science works as a creative enterprise to describe and understand deep truths about the universe, ultimately guided by reproducible experiments.

The primary intent of this course is to experiment with a wide variety of physical phenomena and to give you confidence in the laboratory. You will set up and carry out several complex, open-ended experiments. The experiments change periodically in order to encourage independent exploratory work in the lab. Persistent, creative problem-solving is the goal. After each experiment, you will be asked to present your results in a variety of ways, including oral, written, and poster-based formats.

Structure of the Class: Class meetings are on Thursday morning through Thursday afternoon. Additionally, on Tuesdays and Fridays the laboratory will be open most of the day for you to do research. Students are expected to attend class/work in the lab each Thursday with the rest of the class, and one other substantial block of time during each week, determined in accordance with your lab partner(s). In addition, significant time should be set aside for completing lab write-ups, preparing for presentations, tests and assignments. You will be assigned various experiments together with a target due date. On the due date, students will give short oral presentations describing their work, and turn in written lab reports.

Written and Oral Work: You are required to keep a laboratory notebook for this course in which you will record your day-to-day work. Always begin your entry with the date, time, and name of any lab partners. You are encouraged to work together when taking data and analyzing your results but you may not copy work from one another. If you do not participate in the data acquisition and/or analysis, you should not include it in your notebook. If you include such data in your final write-up or presentation it should include a credit and citation.

The main goal of keeping a lab book is to save time by keeping a careful record of what you have already accomplished. Your notebook should always include:

- A diagram of your experimental setup (label equipment with model numbers)
- Instrument settings
- Sketches of scope traces and other important visual results
- Data and analysis file documentation
- Theoretical derivations and sample calculations and prose descriptions of subtle points
- Reference citations
- An appendix listing ALL instrumentation used in the experiment

A scientist must be able to communicate his or her work to others. You will communicate your work to others by preparing oral/visual presentations. In addition, you will be asked to prepare formal written reports and a poster presentation.

Tinkering: Advanced experimentation often involves careful tinkering (making small adjustments to an experimental parameter while monitoring a signal or response). The fundamental rule of tinkering is that individual parameters should be tested independently. If multiple parameters are adjusted simultaneously, it can be difficult to recover the original signal. I encourage you to try your hand at tinkering – it takes time to develop, but it can be a very useful skill. I will be tinkering with the experiments all semester, but I will try to refrain from tinkering with your apparatus without your permission.

Participation: Oral presentations provide opportunities for you to learn from each other. Obviously, you must be present and attentive during your colleague's presentations for this objective to work effectively. I will monitor and evaluate your participation in this process. Asking good questions is a reliable way of demonstrating that you are engaged in this exchange. Seminar attendance and completion of various surveys will also contribute to your participation grade.

Attending departmental seminars/colloquia/events is part of your participation grade and will broaden your scientific perspective, improve your networking skills, and show you how physics is being practiced in the world beyond GWU. Attendance at 8 or more physics seminars/events is required over the course of the semester. *Ask questions!*

Computer Control, Analysis, and Modeling: In this course we will use various software packages for the acquisition, analysis, and presentation of data, including Mathematica, Tracker, EJS, VPython, Excel, and/or LabVIEW. Further details about the use of these will be made available as things evolve.

Library Work: You will be expected to find and read appropriate books and papers in order to understand the physics underlying your experiments. The *American Journal of Physics* abstract database is a useful resource that should be consulted for every experiment: http://scitation.aip.org/content/aapt/journal/ajp. You might also find *The Physics Teacher* archives useful for most experiments.

Final Project: We will conclude the course with an individual final project. I will try to identify final projects that are a good fit for each student's experience and ability, and I am open to suggestions that you might have for your final project. Please note that the final projects may include evaluation by other faculty in the physics department. Hence, the posters representing the final projects must be available for review by noon on Thursday, December 11th.

Tentative Schedule for Labbook Collection and Class Presentations:

Experiment #1 (Thomson's e/m)	9/12
Experiment #2 (photoelectric effect)	9/26
Experiment #3 (Hydrogen spectra)	10/10
Experiment #4 (precision roller)	10/24
Experiment #5 (speed of light)	11/14
Experiment #6 (Nuclear physics)	12/5
Final Project (extension of #1-6, Ruben's tube, LEDs, coupled/non-linear oscillators, etc.)	12/11

Grading:

Lab-research and notebook	30%
Lab Reports (oral)	20%
Lab Report (written)	20%
Participation/Seminar Attendance/In class work	10%
Midterm Exam	10%
Final Project (paper and poster presentation)	10%

NOTE: IN ACCORD WITH UNIVERSITY POLICY, THE FINAL EXAM PRESENTATIONS WILL BE GIVEN DURING THE FINAL EXAM PERIOD, THE DATE AND TIME OF WHICH IS NOT YET DETERMINED, SO DON"T MAKE WINTER HOLIDAY PLANS TOO EARLY.

CLASS POLICIES

---The grading scale will be no harsher than the standard 10 pt. grading scale:

> 90% is at least an "A-",
> 80% is at least a "B-",
>70% is at least a "C-",
>60% is at least a "D-".

For an absence to be considered excused, "a written excuse from an appropriate agent" is required. See www.gwu.edu/~ntegrity for more info. Unexcused absences on a test day or a presentation day will result in a grade of zero for that test or presentation.

---Attendance is expected. An unexcused absence on a non-major test day will generally result in a zero for the day's participation grade.

---Academic dishonesty of any kind warrants the maximum penalty allowed by the university and the assignment of a failing grade for the course. I personally support the GW Code of Academic Integrity. It states: "Academic dishonesty is defined as cheating of any kind, including misrepresenting one's own work, taking credit for the work of others without crediting them and without appropriate authorization, and the fabrication of information." For the remainder of the code, see: http://www.gwu.edu/~ntegrity/code.html

In accordance with University Policy on Religious Holidays students should notify faculty during the first week of the semester of their intention to be absent from class on their day(s) of religious observance. I will work to provide a fair and alternate assessment in that circumstance, should such be necessary. Failure to notify me in the first week will render such absences unexcused.

SUPPORT FOR STUDENTS OUTSIDE THE CLASSROOM

DISABILITY SUPPORT SERVICES (DSS)---Any student who may need an accommodation based on the potential impact of a disability should contact the Disability Support Services office at 202-994-8250 in the Marvin Center, Suite 242, to establish eligibility and to coordinate reasonable accommodations. For additional information please refer to: http://gwired.gwu.edu/dss/

UNIVERSITY COUNSELING CENTER (UCC) ***202-994-5300***---The University Counseling Center (UCC) is located at 2033 K ST NW Suite 330 and offers 24/7 assistance and referral to address students' personal, social, career, and study skills problems. Services for students include crisis and emergency mental health consultations, confidential assessment, counseling services (individual and small group), and referrals. See **http://counselingcenter.gwu.edu**

Tentative Schedule

Date	Week	Tue	Thur morning	Thur afternoon	Fri (seminar)	Comments
8/24	Week 1			e/m	Welcome!	
8/31	Week 2			e/m		**Labor Day, 9/1**
9/7	Week 3		Presentation 1, e/m	Photoelectric	Ching-Hwa	
9/14	Week 4			Photoelectric		
9/21	Week 5		Presentation 2, Photoelectric	Hydrogen/Bohr		
9/28	Week 6			Hydrogen/Bohr	Mantegno	
10/5	Week 7		Presentation 3, Hydrogen/Bohr	Roller		
10/12	Week 8		Midterm	Roller	Hilborn	
10/19	Week 9		Presentation 4, Roller	Speed of light		
10/26	Week 10			Speed of light		
11/2	Week 11			Speed of light	IRES	
11/9	Week 12		Presentation 5, Speed of light	Nuclear	Jaffe	
11/16	Week 13			Nuclear		
11/23	Week 14		No class	No Class	No Class	**Thanksgiving week**
11/30	Week 15	Make-up day	Presentation 6, Nuclear	Extension activity	Halloween	**Last week of classes**
12/7	Finals	Reading Day		Final presentations (date not yet determined)		Reading Days, 12/8,9
12/14	More finals	Final presentations (date not yet determined)				