SYLLABUS FOR PHYSICS 2BL
A COURSE ON LABORATORY METHODS OF PHYSICS

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Office Hour: Monday 11:30-12:30 or catch me after class on Tuesday

Lecture: Tuesday 8:00-9:20

Labs: Tuesday 9:30, 12:30
Wednesday 9:00, 12:00, 3:00
Thursday 9:30, 12:30
Friday 11:00

Text: J. R. Taylor, An Introduction to Error Analysis.

www: http://hepweb.ucsd.edu/2bl

Introduction to the Course

The objective of this course is to provide you with some instruction and experience in solving problems using the methods of physical science; that is, in performing experiments. For each laboratory, a problem is presented which is to be solved by using a physical apparatus to make measurements.

The stages in the performance of an experiment include: identification and description of the problem, design and construction of equipment to make measurements, learning how to use the equipment, data-taking, and analysis of the data for the solution of the problem.

The final step is to write a report. Our intention is that you gain a little experience in all of these steps so that you will emerge from the course with some first hand experience with this "scientific method."

The equipment that you will use ranges from consumer items available in hardware stores to a few technical instruments such as the ``photogate" timing device. For each experiment, you will receive a statement of the problem to be solved, but you will not receive a cookbook type description of how to solve it. The lectures will present one or more examples of how to do each experiment and a discussion of the experimental problems that are likely to arise in each. You must decide which methods to use in the laboratory.

Procedure

I) Prepare a written plan or **"proposal"** describing how you intend to perform the experiment. It must be no more than two pages long including diagrams and calculations. Lab partners may discuss the proposed experiment together, then prepare and submit separate proposals. Your lab TA will sign off on your proposal before the lab but the proposal will be graded with you lab report. You should write the proposal on paper, which you can later staple into your lab book.

Accurate and concise description of an experiment is an essential part of what we hope you will learn in this course. We suggest you write a first draft of the proposal without attempting to meet the length requirement exactly and then to edit it to make it more accurate and concise.

A copy of the proposal must be submitted to the TA, at the time that you are scheduled for the lab, before you begin the experiment. It should describe:

(1) The question to be answered by the experiment: For example, "Determine which of several fluids provides the greatest reduction of friction between two pieces of steel".

(2) The variables which will be measured and the equipment for measuring them. For the question posed above, the variables might be the force used to drag a steel block across a steel plate at constant velocity and the magnitude of that velocity. The equipment might include a weight and pulley to provide the constant force, a meter stick to measure distances and a pair of photo-gate timers to measure the velocity.

(3) A discussion of the anticipated accuracy of the measurement: For example, time can be measured with the photo-gate timers to about ± 1 millisecond (ms) over an interval as long as a few seconds. Distance can be measured to about ± 0.5 mm with a ruler (for lengths up to about 1 m), or to about ± 0.05 mm with micrometer calipers (for lengths up to about 10 cm). The overall error in the velocity measurement would then be a result of the "propagation" of the errors of both of these measurements through the computation of velocity. The reading assigned in Taylor is to teach you how to do this. If the estimated errors in the experiment exceed the anticipated differences between the various samples, then the experimental design is not adequate to answer the question posed.

4) A description of possible systematic errors and experimental tests to eliminate them. A systematic error would arise if the ``photogate'' timer were miscalibrated. This could be tested and corrected by comparing two or more timers of different types.

II) **Assemble the experimental apparatus** using items that are available in the lab or that you obtain on your own, learn how to use them, and obtain the desired data. Any equipment, simple or complicated, will yield better results as the experimenter gains experience with it. Extensive notes in a laboratory notebook are also an essential part of any experiment. They provide an accurate record of your measurements and procedures. You will need these notes when you write a description of the results of your experiment.

III) **Write a report** in your laboratory notebook and turn it in to the TA before leaving the laboratory. The report should include:

(1) A very brief summary of the experiment as actually performed.

(2) A presentation of the data collected. You should refer to data recorded in your lab book by page number. Some graphical or other summary presentation of the data is usually required.

(3) An analysis of the data. This includes calculations, averages, and fits to data. It's a good idea to do a first pass at the data analysis before your second lab session. (For some (or all) of the experiments, you will be asked to enter your results into a web form to check your calculations and analyze class performance.)

(4) A concise presentation of the results including sources of error, and error estimates. Graphical presentation should be used whenever possible. Hand drawn graphs are usually better than those from your computer. We require ruled lab books just for this purpose.

(5) Draw some conclusions from your analysis. Answer the question posed in the experiment. State whether you achieved the required accuracy and why (not). State how the measurement could have been improved.

If data in your notebook is already entered in readable form, then your report can refer to a page number rather than rewriting the data. In some cases (for example inconclusive results) you may wish to discuss what was wrong with the technique and alternative techniques that you think would yield better results. Data should never be fudged to get the expected result.

Clarity and brevity are the most important requirements for this report. Busy scientists or managers do not have time to wade through unnecessary verbiage or to struggle to understand a badly written report. Because of the heavy emphasis on preparation in this course, the report is intended to require no more than one hour at the end of the laboratory period.

Laboratory Notebooks

We ask that you purchase two quadrille ruled "Comp" notebooks. You will use one book while the TA is grading the other.

Lectures

The lectures will contain material that is essential for satisfactory performance of the experiments. Both the experiments and general error analysis will be covered in the lectures. Your understanding of the lectures will be greatly enhanced if you have read the instruction sheet and any background reading for each experiment and have some preliminary ideas how to proceed.

Homework: Reading & Problems

Homework assignments in Taylor are intended to prepare you for the experiments that you will perform. If you have not learned this material, your laboratory work will not be satisfactory. The assigned problems are shown in the schedule below; they are to be turned in to your lab TA. The homework problems are also good preparation for the test. You may find it helpful and perhaps necessary to solve problems in addition to those listed.

Grades

Class grades will be based 60% on the grades for your proposal, lab notebook, report and web data combined, 5% on the judgment by the instructors about your performance of the experiments, 10% on homework, 5% on in-class experiments, and 20% on the exam. Since laboratory grades tend to cluster tightly around the mean, the exam and homework can be important factors in the final letter grade. A 1-hour test will be given in the lecture room on Tuesday, March 8 (the 10th week). It will test your understanding of the assigned reading and homework in Taylor as well as your understanding of the experiments that you performed. There is no final exam.

A histogram of numerical grades in this class tends to exhibit a fairly narrow peak. This leads to letter grades depending on fairly small differences. A single missed homework assignment or in-class lab can be very important for the final letter grade.

Schedule for the class

Lectures	**Lab Assignment**	**Homework in Taylor**
Week 1 Jan. 4	No Lab this week. Hard work on Lab1 proposal.	Chapters 1,2: error analysis. Problems 2.3, 2.7, 2.18, 2.31. Due at week 2 lab.
Week 2 Jan. 11	Exp. #1, Turn in proposal. Measure the radius of the earth. (First lab Tues. 1/11)	Chapter 3: propagation of errors. Problems 3.7, 3.11, 3.13, 3.40, 3.48. Due at week 3 lab.
Week 3 Jan. 18	Finishes #1, measure g, deduce the mean density, write report.	Chapter 4: mean, standard deviation, and standard deviation of mean. Problems 4.5, 4.13, 4.18, 4.20,4.23. Due at week 4 lab.
Week 4 Jan. 25	Submit proposal #2, measure the wall thickness of a hollow sphere and the densities of a composite cylinder.	Chapter 5: normal distribution function and confidence limits. Problems 5.12, 5.20, 5.22, 5.35. Due at week 5 lab.
Week 5 Feb. 1	Finish #2.	Chapter 6: rejection of data. Problems 6.1, 6.5, 6.6. Due at week 6 lab.
Week 6 Feb. 8	Submit proposal #3, design a critically damped shock absorber	Chapter 7: weighted averages. Problems 7.2, 7.4, 7.6, 7.7. Due at week 7 lab.
Week 7 Feb. 15	Finish #3.	Chapter 8: least squares fitting: problems 8.7, 8.5, 8.10. Due at week 8 lab.
Week 8 Feb. 22	Submit proposal #4, build a voltmeter calibrator	Chapter 12: χ square test. Problems: 12.2, 12.3, 12.14. Due at week 9 lab.
Week 9 Mar. 1	Finish #4	Review
Week 10 Mar. 8	Test in Lecture on Tuesday	

EXPERIMENT #1
MEASURE THE MEAN DENSITY OF THE EARTH

Objective: Measure the mean density of the earth, ρ, using Newton's gravitation law and the previously measured value of the gravitational constant, G = 6.67×10^{-11} (m^3 / kg s^2). From this measurement determine which elements could not constitute the major portion of the earth.

If we were just beginning to try to determine what material is in the deep interior of the earth, a first step might be to determine its density. We expect that the very high pressure near the center of the earth will compress most materials to higher density than they have at the surface; but the differences between the densities of some of the elements are so great that we could at least eliminate some of them from consideration. For example the density of Iron is 7.874 g/cm^3, Lead is 11.35, Mercury is 13.546, Osmium is 22.57. The mean density of the crust of the earth (rocks) is about 2.7 g/cm^3. Much detail is now known about the inner layers of the earth from measurements of the propagation of seismic waves, but this experiment is intended to present you with the problem as it existed before seismic measurements were possible.

Reference: Halliday, Resnick, and Walker, 5th edition. Chapter 14, Gravity. Chapter 16, Oscillations (the simple pendulum section 16.6)

As we will discuss in class, we can determine the density of the earth ρ from the combination of two measurable quantities: the radius of the earth R_e, and the acceleration of gravity g.

$$\rho = \frac{3}{4\pi}\frac{g}{GR_e}$$

We propose to determine R_e by measuring the difference in the time of sunset seen by observers on the beach and on cliffs just above them. How this works will be discussed in class. The equation we will use to calculate R_e is

$$\mathrm{R_e} = \frac{2C}{\omega^2}\left(\frac{\sqrt{h_1}-\sqrt{h_2}}{\Delta t}\right)^2$$

where C is a number (close to 1) which depends on the time of year, h_1 and h_2 are the heights above sea level of the two observers and Δt is the time difference. Other methods are possible and can be proposed by the student.

We can use a pendulum to measure g fairly accurately. The equation for the period of a pendulum is

$$T = 2\pi\sqrt{\frac{l}{g}}$$

Many other methods could also work well enough.

The proposed “time of sunset versus observer elevation” method for measuring the radius of the earth was used by the ancient Greeks. Unless the method provides sufficient accuracy so that the final answer for the density of the earth will be known well enough to eliminate some of the elements, the experiment will not be successful. Thus you must estimate the accuracy expected for the proposed methods in order to decide how to make the measurement.

Perform the experiment safely. Do not go too near the cliffs. Do not drop or kick objects onto (unseen) people below on the beach. Do not stare directly at the sun for this measurement until the top edge is about to disappear.

Note: An alternative for measuring the period of the pendulum is to use the ``photogate" timers which will measure a single swing of the pendulum to better than 1 % accuracy.

EXPERIMENT #2
Measuring Variations of Quantities versus Measuring Absolute Quantities

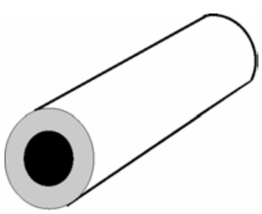
Objective:

1) A manufacturer of racquetballs has discovered that another manufacturer is infringing his trademark. The illegal racquetballs are impossible to distinguish from the real ones by inspecting the outside. However, it has been learned that the illegal manufacturing process is not as uniform as the original one so that the thickness of the shell of the hollow spheres varies from ball to ball by about 10%. You are to devise a simple, fast, and non-destructive method for measuring the variation in thickness of the shell of large numbers of the balls in each shipment arriving at a number of stores, to determine if the variation in thickness is much less than 10%.

The suggested method is to measure the moment of inertia and mass of the balls. The moment of inertia for a hollow sphere of inner radius, r_2, outer radius, r_1, and total mass, M, is: $I = \frac{2M\left(r_1^5 - r_2^5\right)}{5\left(r_1^3 - r_2^3\right)}$

2) Expensive, structural rods for use on a special machine are made in the form of an outer tube and a solid inner cylinder each of a different material. It is important that the diameters of the inner and outer cylinders be the same from sample to sample to within better than 5%. You are to devise a method to measure the thickness and density of the outer and inner cylinders without damaging them so that rods not within specifications will not be used in the machine.

As in the above case, the recommended procedure is to measure the mass and the moment of inertia of the cylinder.



For a solid cylinder, $I_1 = \frac{M_1 R_1^2}{2}$

For a hollow cylinder, $I_2 = \frac{M_2}{2}\left(R_1^2 + R_2^2\right)$

(see textbook section 11-7)

Reference: Halliday, Resnick and Walker, 5th edition, Chapters 11, 12, and 14

Possible methods:

Make a torsion pendulum.

The period of the pendulum, T is related to the torsion constant of the fiber, κ, and the moment of inertia of the pendulum, I, according to: $T = 2\pi\sqrt{\frac{I}{\kappa}}$ (see textbook sect. 16-5)

Use a known moment of inertia such as a solid cylinder or sphere of uniform density and measured mass to determine the torsion constant of the wire from the above equation.

Measure the total mass of the object of interest. Then measure the period of the torsion pendulum with the fiber attached along an axis of symmetry of the object (the axis of the cylinder).

Roll down an inclined plane
Measure the total mass, M, and the radius, R, of the object. Allow it to roll down an inclined plane of angle θ for a distance d (see text section 12-1). Use the photo gate timers to measure the time to travel distance d. From this determine the acceleration and final velocity, v_d, of the object. From energy conservation,

$$Mgd\sin(\theta) = \frac{1}{2}\left(I\omega^2\right) + \frac{1}{2}Mv_d^2$$

where $\omega = v_d / R$. *This technique will not work well for the cylinder because it will not roll straight down the inclined plane without a constraint and the constraint will add friction.*

EXPERIMENT #3
A PROTOTYPE SHOCK ABSORBER

Objective: Construct and test a critical damping system for a spring.

Reference: Halliday, Resnick, and Walter, 5th Edition, chapter 16, special attention to section 16-8 (damped simple harmonic motion)

Discussion: A shock absorber in a car is designed to damp the oscillations of the suspension springs in the car. Without this damping (for example when shock absorbers get old and lose fluid) after a car passes over a bump, it will bounce (oscillate) up and down many times rather than just once. Damping in shock absorbers is obtained by forcing a piston to move through a liquid-filled cylinder with an appropriate amount of fluid flow through or around the cylinder. This provides a drag force that is approximately proportional to the speed with which the piston moves. With this type of damping, the equation of motion for a mass on a spring becomes

$$m\frac{d^2x}{dt^2} = -kx - b\frac{dx}{dt} \quad . \tag{1}$$

(See Eq. 16-39.) The solutions of this equation are of the form

$$x = x_0 \exp\left(-\frac{b}{2m}t\right)\exp\left(it\sqrt{\frac{k}{m}-\frac{b^2}{4m^2}}\right) \tag{2}$$

or in trigonometric notation

$$x = x_0 \exp\left(-\frac{b}{2m}t\right)\cos\left(t\sqrt{\frac{k}{m}-\frac{b^2}{4m^2}}\right). \tag{3}$$

You can prove this by assuming a solution of the form $e^{i\omega t}$*, substitute it in equation (1) and solve for* ω. For weak damping, with

$$\frac{b^2}{4m^2} << \frac{k}{m} \quad , \tag{4}$$

a displacement from equilibrium, as when the car passes over a bump, would result in oscillations that would continue for many cycles, making for an uncomfortable and unsafe ride. If the damping coefficient b is large, with

$$\frac{b^2}{4m^2} > \frac{k}{m} \quad , \tag{4}$$

then the solution of equation (2) is exponential rather than oscillatory, as

$$x = x_0 \exp\left(\left(-\frac{b}{2m} \pm \sqrt{\frac{b^2}{4m^2}-\frac{k}{m}}\right)t\right) \quad . \tag{5}$$

This means that when the mass is suddenly displaced from equilibrium, it will return to its equilibrium position exponentially as a function of time without overshooting or oscillating. Very large values of b would result in a "stiff" suspension for an automobile and would be equivalent to having no springs.
A compromise between these extremes is "critical damping" for which the value of the damping coefficient is chosen so that

$$\frac{b^2}{4m^2} = \frac{k}{m} \quad . \tag{6}$$

In this case a displacement returns to zero exponentially in the shortest time and with the smallest value of b that will do so. Thus the suspension will be as soft as possible without a disturbing oscillation after a bump. (Engineering students will recognize that the critical damping criterion is close to but not exactly the optimal choice.)

In this experiment you are to take an engineering approach in which you first measure the spring constant, k, of a spring. From this you will compute the desired value of b to damp a mass m. You will then set up an experiment to measure b for a variety of damping setups, until you are able to adjust it to the desired value. Finally, this damping mechanism will be attached to the spring/mass system and the combination tested to determine if critical damping has been achieved. In order to measure the damping force, $F_{damping} = -b\frac{dx}{dt}$, you will need to measure the velocity of the damping system as a function of the applied force. In the process you will also confirm that the damping force really is proportional to the velocity as assumed in the above equations.

EXPERIMENT #4
A PROTOTYPE VOLTMETER CALIBRATOR

The units of electric and magnetic quantities are all directly related to the mechanical units of distance, mass, and time. For example, electric charge, Q can be defined in terms of the force between two point charges (Coulomb's law)

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2} \quad . \tag{1}$$

Here, ε_0 is a constant defined to be 8.85×10^{-12}. Electric field, E, is defined as force per unit charge exerted on a test charge, Q_2, so the electric field from a point charge, Q_1, is

$$E = \frac{Q_1}{4\pi\varepsilon_0 r^2} \quad . \tag{2}$$

Voltage is defined to be the potential energy per unit charge of a test charge, Q_2. The potential energy difference between two points is the integral of the force over a path between the points. Thus the voltage difference between two points at distance r_1 and r_2 from a point charge, Q_1, is obtained by integrating equation (2) between the two positions, yielding

$$\Delta V = -\frac{Q_1}{4\pi\varepsilon_0 r_1} + \frac{Q_1}{4\pi\varepsilon_0 r_2} \quad . \tag{3}$$

In this experiment you will construct a device to measure the absolute value of a voltage through the measurement of a force. The actual measurements that you will make will be of mass, distance and time but the result will be a measurement of an electrical potential in Volts. This can be accomplished with the procedure outlined below,

Reference: Halliday, Resnick, and Walker, 5th edition Chapter 25, sections 1 through 5.

Description of the method:

Rather than attempt to simulate point charges to satisfy Coulomb's law, we will measure the force that results from applying a potential (voltage) between capacitor plates. That force is derived from Coulomb's law. Assume that we make two flat plates of radius R, and place them parallel to each other at a separation, d, such that $d \ll R$. Then we can, to some (calculable) accuracy, compute the field as if the plates were infinitely large. If a voltage is applied between the two plates, some charge Q, will be removed from one plate and pushed onto the other. The plates, if originally neutral, will then each have a charge Q of opposite sign. Gauss' law tells us that the electric field between the plates is then given by

$$E = \frac{Q}{A\varepsilon} \quad , \tag{4}$$

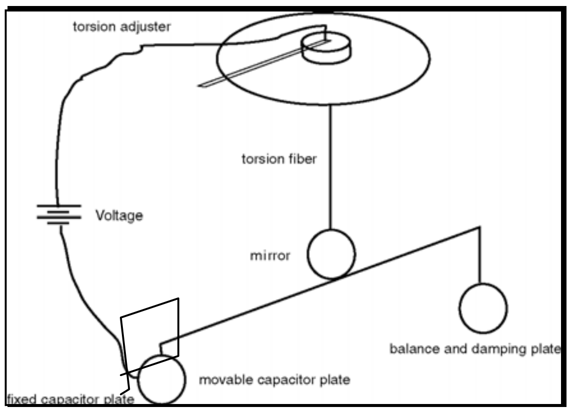
where A is the area of each plate, and ε is the dielectric permittivity of whatever material is between the plates. (ε for air is close enough to that for vacuum, ε_0, so that, to the accuracy of this experiment, the two are equal.) The voltage between the plates is given by the integral of E over the distance between the plates; and since E is constant we have

$$V = Ed = \frac{Qd}{A\varepsilon} \quad . \tag{5}$$

The force between the plates is equal to the charge on one plate times the E field due to the other plate (which is $1/2E_{TOT}$ by symmetry)

$$F = \frac{1}{2}EQ = \frac{1}{2}\frac{Q^2}{A\varepsilon} = \frac{1}{2}\frac{A\varepsilon_0}{d^2}V^2 \quad . \tag{6}$$

Thus if we can measure the force *F*, the area *A*, and the distance *d*, we can determine the absolute value of the voltage applied to the plates.



A simple and accurate method to measure the force is to attach one of the plates to a torsion pendulum, while keeping the other plate fixed. The figure shows a capacitor plate electrically connected to the left arm of the torsion pendulum. (An identical plate is attached to the right arm to balance the pendulum and to damp the pendulum oscillations by placing it in water.)

The torque resulting from the electrostatic force will be *Fl,* where *l* is the horizontal distance between the center of the capacitor plates and the torsion fiber. The angle through which the torsion pendulum will rotate from this torque is $\theta = Fl/\kappa$ where κ is the torsion constant of the suspension (see text section 16-5). The value of κ can be determined by measuring the period of the pendulum, weighing the two plates and computing their moment of inertia, *I*. Then using the expression for the period of a torsion pendulum to solve for κ.

$$T = 2\pi\sqrt{\frac{I}{\kappa}} \tag{7}$$

Measuring the angle of rotation directly would complicate the measurement and reduce its accuracy since the separation *d* between the capacitor plates would also vary with the angle. A better procedure is to hold the separation of the capacitor plates fixed as the voltage between them is increased. This can be done by twisting the top end of the fiber enough to exactly cancel the torque from the applied voltage. The angle of rotation of the top of the fiber is measured by the angle through which the torsion adjuster is rotated. In order to determine accurately that the pendulum remains in the position it had with no voltage applied, we will reflect a light beam from a fixed source off of the mirror onto a screen. The torsion adjuster will then be twisted as the voltage on the capacitor plates is increased so that the image on the screen remains in its original position.

Notice that the torsion fiber and horizontal arm must be metallic in this apparatus so that the voltage difference between the capacitor plates can be applied without an additional wire placing a torque on the suspension.