LABORATORY IV
CIRCULAR MOTION

The problems in this laboratory will help you investigate objects moving in uniform circular motion. This is the same motion that describes satellites in orbit around the earth, or objects whirled around on a rope.

Circular motion can be explained with the same concepts as those used in explaining projectile motion: position, velocity, acceleration, and time. Unlike projectile motion, however, the acceleration of an object undergoing circular motion is *not* constant!

In problems one and two, you will determine the magnitude and direction of acceleration for a rotating platform with uniform circular motion. In problems three and four, you will use acceleration and net force required for circular motion to determine the period of an object whirled horizontally by a rope.

OBJECTIVES:

After successfully completing this laboratory, you should be able to:

- Determine the acceleration of an object undergoing uniform circular motion.

- Use position, velocity, acceleration, and force as vector quantities.

- Use forces to make quantitative predictions for objects in circular motion

PREPARATION:

Read Serway & Vuille Chapter 7 Sections 7.1 to 7.4. Review your results and procedures from Laboratories I, II, and III. Before coming to the lab you should be able to:

- Determine an object's instantaneous and average velocity and acceleration from video images.

- Analyze a vector in terms of its components.

- Add and subtract vectors graphically.

PROBLEM #1:
CIRCULAR MOTION AND ACCELERATION (PART A)

You have been appointed to an amusement ride safety committee for the Mall of America's Camp Snoopy, which is reviewing the safety of a ride that consists of seats mounted on each end of a steel beam. For most of the ride, the beam rotates about its center in a horizontal circle at a constant speed. One committee member insists that a person moving in a circle at constant speed is not accelerating, so there is no need to be concerned about the ride's safety. Another thinks that the person has a constant acceleration when moving at a constant speed. Yet a third argues that the person's acceleration depends on the rate of change of their velocity, not their speed. Since each component of the person's velocity changes with time, their acceleration must change with time. You decide to settle the issue by making a model of the ride and measuring the **magnitude** of the acceleration of different positions on the model when it spins at a constant speed.

EQUIPMENT

For this lab you will have a rotating platform on an A-frame base (top view is shown on the right.) You will also have a stopwatch, a meter stick, a video camera, and a computer with video analysis applications written in LabVIEW™ (VideoTOOL and VideoRECORDER).
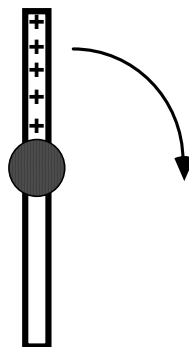
PREDICTION

Does an object moving in a circle accelerate? If so, does the *magnitude* of the acceleration change with time? Explain your reasoning. Use the acceleration equation you derived in the Warm-up to support your claim.

WARM-UP

Read: Serway & Vuille Chapter 7, Section 7.1 to 7.4

1. Make a drawing of the path of an object in circular motion at constant speed. On that path, use a dot to represent the object's position at time t_1. Label this point as O, and draw a vector at O to represent the magnitude and direction of the object's velocity at time t_1. Draw another dot to represent the object's position at a later time t_2, shortly after t_1, and label this point P. Draw a vector at P to show the magnitude and direction of the object's velocity at time t_2.

2. Redraw the velocity vectors with the tail of one vector (point P) at the tail of the other vector (point O). Keep the same size and direction as in the previous drawing. To find the acceleration of the object, you are interested in the change in velocity (Δv).   The change Δv is the increment that must be added to the velocity at time t_1 so that the resultant velocity has the new direction after the elapsed time $\Delta t = t_2 - t_1$. Add the change in velocity Δv to your drawing of the velocity vectors; it should be a straight line connecting the heads of the vectors.

3. On your drawing from question 1, label the distance r from the center of the circle to points O and P. In the limit that the time interval is very small, the arc length distance traveled by the object can be approximated as a straight line. Use this approximation to label the distance traveled by the object along the circle from point O to P in terms of the object's velocity and the elapsed time.

4. The triangle drawn in question 2 (with v and Δv) is similar to the triangle drawn in question 3 (with r and the straight line distance traveled by the object) because they have the same apex angle. Use the relationship of similar triangles to write an equation that connects the sides and the bases of the two triangles.

5. Solve your equation for $\Delta v / \Delta t$ to get an expression for the acceleration in terms of the object's uniform velocity and the distance r.

6. From your equation, is the acceleration of an object in circular motion ever zero? Does the magnitude of the acceleration change with time?

EXPLORATION

Attach the metal platform to the A-frame base and practice spinning it at different speeds. How many rotations does the platform make before it slows down appreciably? Use the stopwatch to measure the total time. Determine which spin gives the closest approximation to constant speed. At that speed, how many video frames will you get for one rotation? Will this be enough to calculate the acceleration as a function of time?

Check to see if the rotating platform is level. Place the apparatus on the floor and adjust the camera tripod so that the camera is directly above the center of the rotating platform.

Practice taking some videos. Choose a position on the platform to represent a person on the spinning ride. How will you make sure that you always click on this same position on the platform when acquiring data?

Decide how to calibrate your video. Where would you put your origin?

MEASUREMENT

Obtain position and velocity data for a specific point on the platform as it spins. Your video should consist of more than two complete rotations. Does the initial position of the rotating platform in your video affect your data? Measure the distance from the center of the platform to rider position with a ruler.

Make sure you set the scale for the axes of your graph so that you can see the data points as you take them. Use your measurements of the total distance the object travels and the total time to determine the maximum and minimum values for each axis.

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ANALYSIS

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Choose a function to represent the graph of horizontal position versus time and another for the graph of vertical position versus time. Can you determine any of the constants from your graph? You can waste a lot of time if you just try to guess the constants in your equations. How can you tell when a complete rotation occurred from each graph? *Hint: Think about what functions might match the general shape of your graph. Are the data linear, or curved? Try some of the menu options. If you still have trouble choosing a function, ask your TA for more hints.*

Similarly, choose a function to represent the graph of horizontal velocity versus time and another for the graph of vertical velocity versus time.

Export your data to a spreadsheet.

The exported data should include horizontal and vertical positions you acquired, and the time stamp. What is a relationship between velocity and position? Make two new columns in your spreadsheet, and use this relationship to calculate the x and y components of the velocity for each pair of successive position measurements.

How can you determine the magnitude of the velocity from the x and y components of the velocity? Make a new column in your spreadsheet of the data that includes the magnitude of the velocity for each point.

Use your equation from the Warm-up to calculate the magnitude of the acceleration of the object in circular motion for each point. Include this in the data table. Is the acceleration zero, or nonzero? Do the values change with time, or remain relatively constant?

Make sure you save a copy of your data, because you might need it for your lab report or the next lab problem.

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CONCLUSION

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Does the magnitude of the acceleration agree with your prediction? Is it constant, or does it change with time? What will you tell the committee? State your result in the most general terms supported by your analysis. What are the limitations on the accuracy of your measurements and analysis?

PROBLEM #2:
CIRCULAR MOTION AND ACCELERATION (PART B)

You have finally convinced the safety committee that a person on the spinning ride at Camp Snoopy accelerates even though the ride moves at a constant speed. The next step for the Committee is to determine the **direction** of the acceleration and thus the direction of the net force on a person so that they can complete their safety proposal.

EQUIPMENT

For this lab you will have a rotating platform on an A-frame base (top view is shown on the right.) You will also have a stopwatch, a meter stick, a video camera, and a computer with video analysis applications written in LabVIEW™ (VideoTOOL and VideoRECORDER).
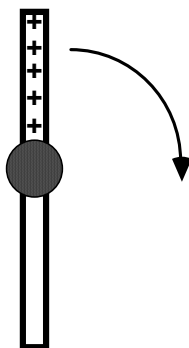
PREDICTION

Determine the direction of the acceleration for an object rotating in a circle at a constant speed. Explain your reasoning.

WARM-UP

Read: Serway & Vuille Chapter 7, Section 7.1 to 7.4

1. Make a drawing of the path of an object in circular motion at constant speed. On that path, use a dot to represent the object's position at time t_1. Label this point as O, and draw a vector at O to represent the magnitude and direction of the object's velocity at time t_1. Draw another dot to represent the object's position at a later time t_2, shortly after t_1, and label this point P. Draw a vector at P to show the magnitude and direction of the object's velocity at time t_2.

2. Redraw the velocity vectors with the tail of one vector (point P) at the tail of the other vector (point O). Keep the same size and direction as in the previous drawing. The change Δv is the increment that must be added to the velocity at time t_1 so that the resultant velocity has the new direction after the elapsed time $\Delta t = t_2 - t_1$. Add the change in velocity Δv to your drawing of the velocity vectors; it should be a straight line connecting the heads of the vectors.

3. Recalling the relationship between change in velocity and acceleration, construct a vector that represents the direction and magnitude of the *average acceleration* between the pair of velocities. Would the direction of the acceleration be different for very close points on the object's path?

4. Repeat steps 1-3 for two different neighboring positions on the object's circular path. Is the direction of the acceleration for this pair of velocities the same, or different as before? What can you conclude (in general) about the direction of acceleration?

EXPLORATION

If you have already done Problem #1, you can use that video and data and move on to the analysis. If not, do the exploration in Problem #1.

MEASUREMENT

If you have already done Problem #1, you can use those measurements and move on to the analysis. If not, do the measurement given in that Problem.

ANALYSIS

Use the spreadsheet data values you exported to determine the approximate velocity vector components at each position of the object's motion. Why are the velocity vectors approximate? Make a large drawing of the motion of the object, labeling the position and velocity components for a few of the consecutive values. Show the direction of the velocity at these points. You should use as many dots as needed to convince yourself and others of the direction of the velocity of the object.

Use the velocity vectors (and the change in the velocity vectors) to determine the approximate direction of the acceleration vectors at each position. Why are the acceleration vectors approximate? You should use as many dots as needed to convince yourself and others of the direction of the acceleration of the object.

CONCLUSION

What is the direction of the acceleration for an object rotating with a constant speed? What will you tell your committee members? How fast can the ride spin before harming the riders? Is this answer consistent with your prediction? Why or why not?

PROBLEM #3:
ROTATIONAL PERIOD AND FORCE (PART A)

Another popular amusement ride consists of seats attached to ropes which are then whirled in a circle. As a member of the safety committee you are asked to determine the relationship between the force exerted by the rope to keep the riders rotating approximately horizontal to the ground and the period of rotation. Specifically, you must determine how the force required to keep an object rotating at a constant speed changes depending on the object's rotational period. This is an essential study because it will help determine how fast the rotation can be without snapping the ropes.

EQUIPMENT

You will use a rubber stopper attached to one end of a string. The string is threaded through a cylindrical handle and a hanging washer is attached to the other end of the string. By gently rotating the vertical handle, you can make the rubber stopper move with a constant speed in a horizontal circle around the handle. You will also have a stopwatch, a meter stick, and a triple-beam balance.

In this lab problem you will have several washers available to vary the hanging mass on the string.
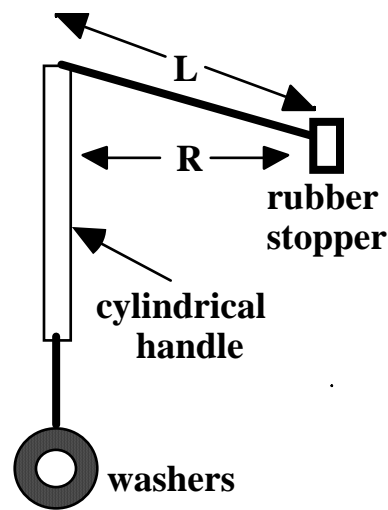
PREDICTION

Write an equation for the period of rotation for the stopper moving at a constant speed in a nearly horizontal circle. The equation should be in terms of the mass of the washer (M), mass of the stopper (m), and the length of the string from handle to stopper (L).

Determine how the force exerted on the string holding the stopper depends on the period of rotation. Use this equation to sketch a graph of the force on the string versus the period of rotation.

WARM-UP

Read: Serway & Vuille Chapter 7, Sections 7.1 to 7.4

1. Make a sketch of the problem situation similar to the one in the Equipment section. Indicate the path taken by the rubber stopper. In this case you may want to make two pictures: a top view and a side view. Label the length of the string between the top of the

cylinder and the rotating stopper, the mass of the rubber stopper and hanging washer(s), and the velocity and acceleration vectors of the stopper.

2. Because gravity pulls downward on the stopper, the string slopes slightly downward in the picture. For simplicity, in this problem you can assume the string is approximately parallel to the ground. (The vertical forces on the stopper are small enough in comparison to the horizontal force(s) to be neglected.) Draw a new side view picture with the stopper moving purely horizontally.

3. Draw <u>separate</u> free-body diagrams of the forces on the stopper and the forces on the hanging washer(s) while the stopper is moving horizontally. What assumptions, if any, are you making? Assign symbols to all of the forces, and define what they represent next to your diagrams. For easy reference, it is useful to draw the acceleration vector for the object next to its free-body diagram. It is also useful to put the force vectors on a separate coordinate system for each object (force diagram). Remember that on a force diagram, the origin (tail) of all vectors is at the origin of the coordinate system.

4. For *each* force diagram (one for the stopper and another one for the washers), write down Newton's 2nd law in both the x and y directions. What is the direction of the acceleration of the stopper? Your answer will depend on how you define your coordinate system.

5. Write down a relationship between the weight of the hanging washer(s) and the force acting on the stopper by the string. What is the force acting on the *string*?

6. How can you determine the stopper's centripetal acceleration from its speed? How can you determine the stopper's speed from its period? Combine these relationships with the ones in questions 4 and 5 to write an equation for the stopper's period in terms of the mass of the hanging washers (M), the mass of the stopper (m), and the length of the string from the handle to the stopper (L).

7. Use the relationship from question 5 to write an equation for the force on the *string* in terms of the stopper's period of rotation (T), the mass of the stopper (m), and the length L. Use this equation to sketch a graph of the force on the string versus the period of rotation.

EXPLORATION

TRY NOT TO HIT YOURSELF, YOUR CLASSMATES, OR YOUR LAB INSTRUCTOR!
The rubber stopper could give someone a serious injury. Wear the safety goggles provided to protect your eyes.

Assemble the apparatus as shown in the Equipment section. While rotating the rubber stopper, the length of the string between the top of the cylinder and the rotating stopper should be held constant. Mark the string with a pen or tape to ensure this.

Hang a different number of washers from the string to see how it feels when you rotate the rubber stopper. Decide on the range of washer masses that you need to use to determine the relationship between the period of rotation and the mass of hanging washers. You may need to refer to your predicted relationship to determine the range of masses to use.

Can you measure one period of rotation accurately with a stopwatch? If not, how many rotations are necessary to accurately measure the period? For very fast rotations, you might need to use many rotations to minimize uncertainty. Try it.

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MEASUREMENT

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Record the length of string between the top of the cylinder and the rotating stopper, and the mass of the rubber stopper. Include measurement uncertainties.

For a range of different hanging washers, measure the period of the rubber stopper with a stopwatch. Record your measurements of the period associated with each hanging mass in an organized way.

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ANALYSIS

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Using your prediction equation, calculate the predicted period for each hanging mass you used.

What is the relationship between the hanging washer mass and the tension force on the string? Calculate the force on the string for each of your measured periods.

Make a graph of the force on the string versus the *measured* period of rotation for your data. On the same graph, plot the force on the string versus the *predicted* period of rotation.

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CONCLUSION

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What are the limitations on the accuracy of your measurements?

How does the force required to keep an object rotating at a constant speed change depending on the object's rotational period? Explain your answer.

PROBLEM #4:
ROTATIONAL PERIOD AND FORCE (PART B)

As an extension of your study in Problem #3 you are now asked to determine how the period of rotation of a rider depends on the rider's mass when the radius of rotation is kept the same. This is important since obviously not all theme park visitors weigh the same.

EQUIPMENT

The apparatus you will use has a rubber stopper attached to one end of a string. The string is threaded through a cylindrical handle and a hanging washer is attached to the other end of the string. By gently rotating the vertical handle, you can make the rubber stopper move with a constant speed in a circle around the handle. You will also have a stopwatch, a meter stick, and a triple-beam balance.

In this lab problem you will have several rubber stoppers of different masses.
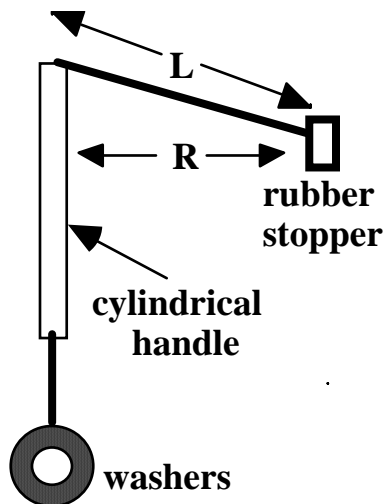
PREDICTION

Write an equation for the period (T) of rotation for the stopper moving at a constant speed in a nearly horizontal circle. The equation should be in terms of the mass of the washer (M), mass of the stopper (m), and the length of the string from handle to stopper (L).

Use this equation to sketch a graph of the period of rotation vs. mass of the stopper.

WARM-UP

Read: Serway & Vuille Chapter 7, Sections 7.1 to 7.4

If you have completed part A, refer to your answers to Warm-up questions 1 – 6 from problem #3.

1. Make a sketch of the problem situation similar to the one in the Equipment section. Indicate the path taken by the rubber stopper. In this case you may want to make two pictures: a top view and a side view. Label the length of the string between the top of the cylinder and the rotating stopper, the mass of the rubber stopper and hanging washer(s), and the velocity and acceleration vectors of the stopper.

2. Because gravity pulls downward on the stopper, the string slopes slightly downward in the picture. For simplicity, in this problem you can assume the string is approximately parallel to the ground. (The vertical forces on the stopper are small enough in comparison to the horizontal force(s) to be neglected.)   Draw a new side view picture with the stopper moving purely horizontally.

3. Draw <u>separate</u> free-body diagrams of the forces on the stopper and the forces on the hanging washer(s) while the stopper is moving horizontally. What assumptions, if any, are you making? Assign symbols to all of the forces, and define what they represent next to your diagrams. For easy reference, it is useful to draw the acceleration vector for the object next to its free-body diagram. It is also useful to put the force vectors on a separate coordinate system for each object (force diagram). Remember that on a force diagram, the origin (tail) of all vectors is at the origin of the coordinate system.

4. For *each* force diagram (one for the stopper and another one for the washers), write down Newton's 2nd law in both the x and y directions. What is the direction of the acceleration of the stopper? Your answer will depend on how you define your coordinate system.

5. Write down a relationship between the weight of the hanging washer(s) and the force acting on the stopper by the string. What is the force acting on the *string*?

6. How can you determine the stopper's centripetal acceleration from its speed? How can you determine the stopper's speed from its period? Combine these relationships with the ones in questions 4 and 5 to write an equation for the stopper's period in terms of the mass of the hanging washers (M), the mass of the stopper (m), and the length of the string from the handle to the stopper (L).

7. Use this equation to sketch a graph of the period of rotation versus the mass of the stopper.

EXPLORATION

TRY NOT TO HIT YOURSELF, YOUR CLASSMATES, OR YOUR LAB INSTRUCTOR!
The rubber stopper could give someone a serious injury. Where the safety goggles provided to protect your eyes.

Assemble the apparatus as shown in the Equipment section. While rotating the rubber stopper, the length of the string between the top of the cylinder and the rotating stopper should be held constant. Mark the string with a pen or tape to ensure this.

Decide how many washers you want to hang on the string. Make sure this number of washers enables you to produce good results for all of the different stopper masses that you will use.

Can you measure one period of rotation accurately with a stopwatch? If not, how many rotations are necessary to accurately measure the period? Try it.

MEASUREMENT

Record the length of string between the top of the cylinder and the rotating rubber stopper you will use, and the mass of the rubber stopper. Include uncertainties.

For a range of different masses of rubber stoppers, measure the period of the rubber stopper with a stopwatch. Record your measurements of the period associated with each stopper mass in an organized way.

ANALYSIS

Using your prediction equation from the Warm-up questions, calculate the *predicted* period for each stopper mass you used.

Make a graph of the *measured* period of the system vs. the mass of the rubber stopper. On the same graph, plot the *predicted* period vs. the mass of the rubber stopper.

CONCLUSION

How does your predicted graph compare to the graph you found from your measurements? Explain any differences.

What is the limitation on the accuracy of your measurements? How does the period of rotation of the rubber stopper depend on its mass?

☑ CHECK YOUR UNDERSTANDING

1. A ball on the end of a string travels in a clockwise circle at constant speed. On the figure at right, draw the vectors requested below, label them clearly, and explain your choices.
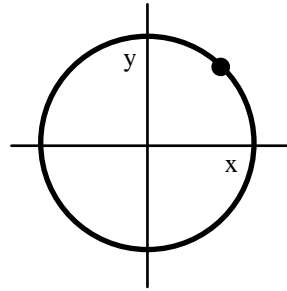
    a. The position vector for the ball.
    b. The velocity vector for the ball.
    c. The acceleration vector for the ball.

2. Two beads are fixed to a rod rotating at constant speed about a pivot at its left end, as shown in the drawing at right.
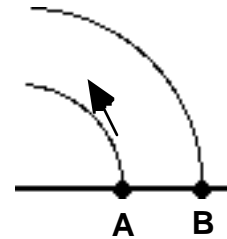
    a. Which bead has the greater speed? Explain your reasoning.

   b. Which bead has an acceleration of greater magnitude? Explain your reasoning.

3. Two racing boats go around a semicircular turn in a race course. The boats have the same speed, but boat A is on the inside while boat B is on the outside, as shown in the drawing.
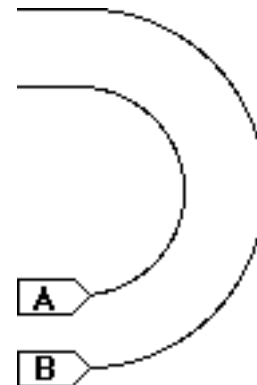
    a. Which boat gets around the turn in less time? Explain your reasoning.

    b. Which boat undergoes the greater change in velocity while in the turn? Explain your reasoning.

    c. Based on the definition of acceleration, which boat has the greater acceleration while in the turn? Explain your reasoning.

    d. Based on the equation for centripetal acceleration, which boat has the greater acceleration while in the turn? Compare your answer to part c. Explain your reasoning.

4. A planet moves in a uniform circular orbit around the sun, which exerts a gravitational force F_G on the planet. What additional *force(s)* act on the planet?

    (a) A force of motion in the direction of the circular orbit.
    (b) A centrifugal force acting outward (away from the sun).
    (c) A centripetal force acting inward (toward the sun).
    (d) A normal force.
    (e) The gravitational force (F_G) is the only force.
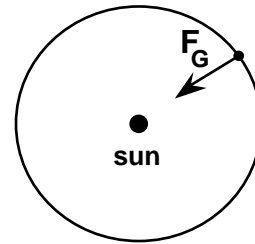
    Explain the reason for your choice.

5. Centripetal force is simply a special name that we give to the net force that produces a centripetal acceleration. In each case listed below, identify the force, force component, or combination of forces that provides the centripetal force. Draw a force diagram for each case and discuss it.

    a. A child on a swing travels in a circular arc. Analyze the situation at the bottom of the swing.

    b. A car travels around a circular, flat, horizontal curve.

    c. A person stands on the equator of the earth, traveling in an earth-sized circle as the earth rotates.

    d. A car travels in a circular curve that is banked inward.

    e. A ball rolls inside a circular hoop that is placed on a horizontal table.

    f. A car drives over the top of a circular hill.

    g. A tennis ball rolls without slipping over the top of a basketball

TA Name:

PHYSICS 1101 LABORATORY REPORT

Laboratory IV

Name and ID#:

Date performed: _____ Day/Time section meets: _____

Lab Partners' Names: _____

Problem # and Title: _____

Lab Instructor's Initials: _____

Grading Checklist	Points
LABORATORY JOURNAL:	
PREDICTIONS (individual predictions and warm-up completed in journal before each lab session)	
LAB PROCEDURE (measurement plan recorded in journal, tables and graphs made in journal as data is collected, observations written in journal)	
PROBLEM REPORT:*	
ORGANIZATION (clear and readable; logical progression from problem statement through conclusions; pictures provided where necessary; correct grammar and spelling; section headings provided; physics stated correctly)	
DATA AND DATA TABLES (clear and readable; units and assigned uncertainties clearly stated)	
RESULTS (results clearly indicated; correct, logical, and well-organized calculations with uncertainties indicated; scales, labels and uncertainties on graphs; physics stated correctly)	
CONCLUSIONS (comparison to prediction & theory discussed with physics stated correctly ; possible sources of uncertainties identified; attention called to experimental problems)	
TOTAL(incorrect or missing statement of physics will result in a maximum of 60% of the total points achieved; incorrect grammar or spelling will result in a maximum of 70% of the total points achieved)	
BONUS POINTS FOR TEAMWORK (as specified by course policy)	

* An "R" in the points column means to rewrite that section only and return it to your lab instructor within two days of the return of the report to you.