**PRELAB: ROTATIONAL KINEMATICS AND TORQUE**

1. Perform the calculations in the “Prelab exercise” from Investigation 1 below. Include the answers to questions Q1-1, Q1-2 and Q1-3.

2. Make a prediction about what will happen in step 2 of Investigation 2. Explain the reasoning behind your prediction.

3. Make a prediction about what will happen in step 3 of Investigation 2. Explain the reasoning behind your prediction.

4. Make Prediction 3-1. Explain the reasoning behind your prediction.
Rotational Kinematics and Torque

**Topic:** Rotational kinematics, torque

**Overview:** The wheels on a cart, the hands on a clock, propellers and merry-go-rounds are examples of things that rotate on a fixed axis. In the first part of this lab, you examine this type of motion in some detail. You will explore the definitions of angular velocity and angular acceleration by examining the motion of a turntable.

In the second part of the lab, you will investigate the concept of torque using a yo-yo (in a manner somewhat different than the designers intended).

In the third investigation, you will examine how the distribution of mass of an object affects its rotational motion.

**Writing it up:** Throughout this handout, you will be asked to answer questions, sketch graphs and diagrams, and do calculations. Write these things on the handout *as you go through the experiment.*

**Safety/Equipment Tips**

Excel is very handy for the repeated calculations in Investigation 3.

**Room setup notes (for TA’s)**

The “turntable” in Investigation 1 can be almost anything circular that spins on a fixed vertical axis, including a vertically oriented wheel, a merry-go-round, a lazy Susan... All that’s required is that it can spin for at least a few turns before stopping. Some frictional torque is desirable, since students will measure angular acceleration.

The “turntable” in Investigation 3 must be a lazy Susan (i.e. a rotating surface mounted on a fixed base, often used in kitchens). The top surface (not necessarily circular) must be large enough so that masses can be placed on its surface and moved, leading to a substantial change in the lazy Susan's moment of inertia. Bearings with low friction are desirable, but not imperative. The top surface should not be slick (so that the weights do not slide along the surface as the lazy Susan turns).

**Investigation 1: Spinning wheels**

In this investigation, you will use a turntable to investigate the motion of a rotating object. As you do this investigation, keep in mind that there is a distinction between the motion of a point on a rotating object and the overall motion of the rotating object.
You will need some type of simple turntable (a lazy Susan will work), a wall clock (with a second hand), a ruler, a protractor (perhaps) and a stopwatch for this Investigation.

Activity 1-1: Describing Rotational Motion

When a rigid object is rotating, it is inconvenient to use concepts like velocity and acceleration without some modification. Consider the example of the second hand on a clock. As the tip of second hand moves, its velocity vector is always changing (since the direction of motion is constantly changing). Furthermore, different parts of the second hand move at different speeds. The tip races around the dial while points near the center of the second hand hardly move at all. What is needed is a new kinematics vocabulary based on angles rather than distances.

Angular velocity is a vector that describes how fast an object rotates around a fixed axis. If the object rotates through an angle $\Delta \phi$ in an amount of time $\Delta t$, the magnitude of the average angular velocity vector $\vec{\omega}_{\text{ave}}$ is

$$|\vec{\omega}_{\text{ave}}| = \frac{\Delta \phi}{\Delta t}$$

The direction of the angular velocity vector is given by the orientation of the axis the object is rotating around and the direction of the rotation. The angular velocity vector is always along the axis of rotation. To find the direction of $\vec{\omega}$, use your right hand. Curl your fingers with the motion of the rotating object, and your thumb will naturally point in the direction of $\vec{\omega}$.

1. Prelab exercise: Observe the motion of the second hand on a clock. Determine the magnitude of the average angular velocity of the second hand of the graph. Express your answer in radians per second and in degrees per second. Determine and record the direction of $\vec{\omega}_{\text{ave}}$.

   Q1-1: Do all points on the second hand have the same angular velocity? Explain.
   Q1-2: What angle does the second hand sweep out in 5 sec? in 10 sec? Express your answers in both radians and degrees. What assumption are you making in this calculation?
   Q1-3: You might be tempted to use the word “clockwise” to describe the direction of $\vec{\omega}$. What drawback does this have? (Hint: Consider two people looking at the clock: one looking at the second hand’s motion from the front and one looking at the motion from the back. Would the two people agree?) Does the direction defined by the right hand rule above have the same drawback? Explain.

2. Give the turntable a counterclockwise spin, so that it turns around a few times before stopping. Use the stopwatch to estimate the magnitude of its average angular velocity during the first few turns. Express your answer in radians per second. Briefly describe the measurements you made. Record the direction of the average angular velocity vector.

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You probably noticed that the turntable slows down as it spins. As you might expect from your experience with translational kinematics, changes in angular velocity are described by angular acceleration. Not surprisingly, angular acceleration $\vec{\alpha}$ is defined as the change in the angular velocity vector per unit time:
In general, angular acceleration vector $\vec{\alpha}$ will rarely point in the same direction as the angular velocity $\vec{\omega}$. If the axis of rotation does not change during the motion (as is the case throughout this lab), the angular acceleration $\vec{\alpha}$ will be directed along the axis of rotation (although not necessarily in the same direction as $\vec{\omega}$).

3. Give the turntable another counterclockwise spin, so that it turns around a few times before stopping. How can you determine the magnitude of the angular acceleration while the turntable is slowing down? Devise a plan to measure the angular acceleration using the available equipment. Outline the plan below. Describe exactly what things you will measure, how you will use these numbers to determine the value for $|\vec{\alpha}|$ and list any assumptions you make about the turntable’s motion.

Have an instructor check your plan before continuing.

4. Execute your plan. Record the measurements and calculations below. Express your answer in radians per second squared.

Q1-4: When you gave the turntable a spin, it had an angular acceleration. During the time interval the turntable was speeding up, what was the direction of the angular acceleration vector? Was the magnitude of $\vec{\alpha}$ during this time interval greater than, less than or equal to the angular acceleration that the turntable had while it is slowing down? Explain.

Activity 1-2: Applying Torque

How do you change an object’s angular velocity? From Newton’s laws, you know a force must be applied to change an object’s linear velocity. It seems reasonable that there should be some rotational analog of force that changes the angular velocity of objects. Intuitively, it makes sense that if you twist on something, its angular velocity will change (imagine spinning a top). This twist is called torque.
In this activity you will investigate how forces and torques are related. You will also explore the definition of the torque vector and its relationship to angular acceleration.

You can give the turntable a spin by applying force. However, the same force can have very different results, depending on how and where the force is applied. Consider the same force exerted at various points on the rim of the turntable:

Q1-5: In which situation does the force produce the smallest angular acceleration? the largest? Explain. Try it and see.

Q1-6: How does the point at which the force is applied influence the direction that the angular acceleration vector points? Test your ideas with the equipment.

Q1-7: Suppose the same force is applied at a point closer to the axis of rotation. What affect would this have on the angular acceleration? Explain. Try it and see.

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Investigation 2: Torque and the Yoyo

In this investigation, you will examine how forces and torques act on a yoyo to cause both linear and angular acceleration.

1. Hold the yoyo so that the string is to the left of the axis of rotation as you face it, as shown. Release the yoyo, holding onto the string. Observe the motion as it falls and record what you see. Some questions to consider as you observe the motion: Which way does the yoyo go? Which way does the yoyo rotate? Does the angular velocity change?
Q2-1: Which way does angular velocity vector point? Explain.

Q2-2: Is there angular acceleration? Use your observations to support your claim.

Q2-3: In which direction does the angular acceleration vector point? Explain how you know from your observations.

Q2-4: Identify the forces acting on the yoyo. Which one(s) are responsible for the rotation of the yoyo? Explain how you inferred the answer to this question. [Hint: Think about what would happen if each force acted alone].

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2. Place the yoyo on the table as shown below. Pull gently upward on the string. Observe the motion and record what you see. Some questions to consider as you observe the motion: Which way does the yoyo rotate? Which direction does the yoyo go? Does the angular velocity change?

Q2-5: Identify all the forces acting on the yoyo. Which one(s) exert a torque on the yoyo? Which one(s) don’t? Explain how you inferred the answers to this question.

Q2-6: Which force produces the strongest torque? Explain how you know.
Q2-7: In which direction does the net torque vector point? Explain how you know.

3. Place the yoyo on the table as shown below. Pull gently on the string along the table in the direction shown. Observe the motion and record what you see. Some questions to consider as you observe the motion: Which way does the yoyo rotate? Does the angular velocity change?

Q2-8: Identify the forces acting on the yoyo. Which one(s) exert a torque on the yoyo? Which one(s) don’t? Explain how you inferred the answers to this question.

Q2-9: Which horizontal force is stronger: friction or tension? Explain how you know.

Q2-10: Which horizontal force produces the stronger torque: friction or tension? Explain how you know.

Q2-11: Compare your answers to the previous two questions. Is there a contradiction? Explain how this is possible.
Quantitative challenge:

What happens as you slowly increase the angle θ between the string and horizontal? You might think that there is some critical angle where the behavior of the yoyo changes. For angles below this critical value, the yoyo behaves as it did when you pulled horizontally. For angles above the critical value, the yoyo behaves as it did when you pulled up on the string. Predict the value of this critical angle on theoretical grounds, using only the physical attributes of the yoyo. Carefully show the reasoning behind each step of the derivation. Test the prediction. How does the yoyo behave at the critical angle?

Investigation 3: Spinning wheels revisited

In this investigation, you will investigate how the distribution of mass affects the rotational motion of an object.

Safety Note: Take care not to spin the turntable so fast that the weights fly off the surface of the turntable.

1. Place four identical weights near the center of the turntable. All of the weights should be about the same distance from center of the turntable. Give the turntable a spin and allow it to slow down. Observe the motion.

Prediction 3-1: Suppose you move the masses from the middle of the turntable to the edge. Again you give it a spin and allow it to slow down. How will the motion differ from the motion in the previous situation when the masses were near the middle of the turntable? Explain the basis for your prediction.
2. Check Prediction 3-1 qualitatively. Does the motion seem to die out more or less quickly when the weights are near the edge of the turntable?

In lecture, you probably learned that the same torque applied to an object can cause different amounts of angular acceleration, depending on the object’s moment of inertia: \( \tau = I\alpha \). The moment of inertia is a measure of an object’s resistance to angular acceleration about a given axis. You can think of moment of inertia as “rotational mass.” The larger an object’s moment of inertia about some axis, the more resistant the object is to changes in its angular velocity about that axis.

Q3-1: According to your observation of the turntable’s motion, how does moving the masses to the edge of the turntable affect the moment of inertia of the turntable? What assumption are you making about the torque that causes the turntable to slow down?

3. Check Prediction 3-1 quantitatively. Use the method you devised in Investigation 1 to measure the angular acceleration of the turntable while it is slowing down. You will need reasonably reliable values for \( |\alpha| \), so you should repeat each measurement several times. Record your data below.

<table>
<thead>
<tr>
<th>Masses near the center</th>
<th>Masses near the edge</th>
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Revised 11/4/04 by DSA for P15
Q3-2: Which configuration has the larger acceleration value? Does this match your expectation? Explain.

Q3-3: Is it possible to conclude which configuration has the larger angular acceleration, given the fact that acceleration values vary from run to run? Explain, using your data to back up your assertion. (Put another way: Is it reasonable to reject the possibility that the angular accelerations for the two configurations are equal, given your data?)

Q3-4: Compare the acceleration results for each configuration. Which set of data is more trustworthy? Explain, using your acceleration data to back up your assertion.

Discuss your results with an instructor before continuing.

In lecture you may have learned that the moment of inertia for a collection of point particles can be calculated from the positions of the masses relative to the axis of rotation: \( I = \sum m_i r_i^2 \) where \( r_i \) is the distance from the point mass \( m_i \) to the axis of rotation. For extended objects, this sum becomes an integral: \( I = \int r^2 \, dm \).

4. Measure the relevant distances and masses to estimate the moment of inertia of the turntable plus masses system for each configuration of masses. Record the data and perform the necessary calculations below. List any simplifying assumptions you make in your calculations.
The moment of inertia for a square sheet of material of uniform density spun about its center can be found by doing an integral. The result is $I = \frac{1}{6} ML^2$, where $L$ is the length of the square and $M$ is its mass).

Q3-5: The two configurations have the same total mass. Do the moments of inertia? Is there a contradiction? Explain.

Q3-6: Calculate the net torque acting on the turntable for each configuration. Compare the results. Is the net torque acting on the wheel larger for one of the two configurations? If so, which one? Do these results match your expectations? Explain.

Q3-7: Is it reasonable to reject the possibility that the net torque is the same for the two configurations, given the fact that acceleration values vary from run to run? Explain, using your data to back up your assertion.