I. Before you come to lab.

- Read through this handout and the supplemental
- Do the pre-lab question from HW5. Turn it in to your section TF by Tuesday before class, but also bring a copy of your solution to lab.

II. Learning Objectives

1. Apply conservation of energy with rotational motion.
2. Understand the connection between angular velocity and linear speed.
3. Get an intuitive understanding of torque and angular momentum.

III. Materials

You will be sharing materials with another group for this lab. Except for the computer, there is one of the following for every two tables.

- Stool on rotating platform

Use this four-legged stool that sits on a rotating platform with low friction to explore angular momentum phenomena, and to measure your moment of inertia.

- Stopwatch (2)

Use it to time how long it takes for you to complete several revolutions while spinning on the stool.

- String

It's just string.

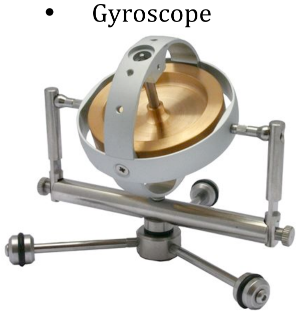
- 1-kg weights (3)

Use one of these weights as the hanging mass on the moment of inertia setup. Hold the other two in your hands (one in each hand).

- Bicycle wheel

This bicycle wheel has handles along the axis of rotation so you can hold on to it while it spins. Use it with the spinning stool to explore (and experience!) conservation of angular momentum and precession.

- Gyroscope



Use this gyroscope on a gimbal mount that allows it to rotate freely along two axes of rotation (horizontal and vertical) to explore the phenomenon of precession.

- Rotary motion sensor

- Computer with Logger Pro

You have used this before.

IV. Warm up (30 minutes)

You probably have seen how ice dancers turn themselves into a fast spinning motion on ice, or how divers do fast summersaults and then nearly stop the rotation before touching the water. How is this possible? (This is a rhetorical question, which you will be able to answer by the end of lab.)

Say you are sitting on a rotating chair holding two dumbbells, one in each hand, with your arms stretched to the side. Your friend gives you a push, and you and the chair start rotating. You then bring your arms in, close to your body. **Describe what you think will happen next.**
A:

Suppose you know the moment of inertia of you sitting on the chair, holding the dumbbells with your arms stretched out, as well as the moment of inertia of you sitting on the chair, holding the dumbbells close to your body. **How will your angular velocity change in the case described above, if at all?** Write down an expression for calculating your final angular velocity.
A:

Suppose you are sitting on a rotating chair holding a bicycle wheel by the axle. The wheel is vertical, and it is spinning so that the top edge is rotating away from you. For a picture of this, check out the supplemental file. **What do you think will happen if you turn the bicycle wheel to the left into the horizontal position? What do you think will happen if you turn the wheel back to being vertical?**
A:

You are once again sitting on a rotating chair holding a bicycle wheel by the axle. This time the wheel is horizontal and it is spinning. The chair is not rotating. **What do you think will happen if you turn the wheel by 180 degrees, so that it is horizontal in the opposite direction? What do you think will happen if you turn the wheel back to its original orientation?**
A:

V. Procedure (150 minutes)

Tell us who you are (picture, names, and emails, please)
A:

There are two parts for this lab. Half of the groups will do part 1 first and part 2 second, while the other half will do part 2 first and part 1 second.

Part 1: Rotation and angular momentum (110 minutes)
In this part of the lab you will work with a rotating stool and explore various aspects of rotation and angular momentum. The stool is mounted on a ball bearing with low friction, so that it does not immediately slow down its rotation.

Part 1 Data Collection (50 minutes)

Take all the necessary data first, so that the equipment will be free for another group to use.

At your table (or at a table next to yours) you will find the setup described in the supplemental file for this lab for measuring your moment of inertia. Make sure the Rotary Motion Sensor is connected to the LabQuest Mini interface for the computer at your side of the table.

Take the necessary data for measuring the moment of inertia of you sitting on the stool holding two 1-kg weights close to your body and of you sitting on the stool holding two 1-kg weights in your hands with your arms stretched to the side. Instructions for taking data using this setup are found in the supplemental file; you only need to do this for one person. Make sure you save your data, since you will be doing the analysis later in the lab.

Before doing the following, make sure the rotating stool is no longer connected to the rotary motion sensor.

Sitting on a chair with two dumbbells, one in each hand, and arms stretched to the side, give yourself a push and start rotating. Slowly bring your arms close to your body. **What happens?** Everyone should do this once, but only take data (see below) for the person whose moment of inertia you measured above.
A:

With your arms stretched to the side, have someone from your team time how long it takes to go 2 full rotations. Bring your arms close to your body and have another person time how long it takes you to go 2 full rotations.
Time for 2 rotations (arms stretched), with uncertainty:
Time for 2 rotations (arms close to body), with uncertainty:

Now you will use the bicycle wheel mounted on handles to explore the concept of conservation of angular momentum. Spin up the bicycle wheel as fast as you can. Then sit on a stool.

Start with the chair at rest and the bicycle wheel vertical. The wheel should be spinning so that the top edge is rotating away from you. Turn the wheel to the left or to the right so that it is now horizontal. **What happens?**
A:

How does this compare with your predictions from the warm up?
A:

Now start with the chair at rest and the spinning bicycle wheel horizontal. Turn the wheel by 180 degrees until it is horizontal with the opposite orientation. **What happens?**
A:

What happens if you turn the wheel back to the initial orientation?
A:

What happens if you turn the wheel 180 degrees the other way?
A:

Part 1 Analysis: Measure your moment of inertia (60 minutes)
The rest of this part's instructions will guide you in doing the necessary calculations for determining your moment of inertia. You will not collect any more data for part 1, so you can let the other team collect data.

Look at the Angle vs. Time graph for the data collected when you were holding your **arms close to your boy**. **What shape does the graph have?** Is it linear, quadratic, exponential, other?
A:

Fit the **Angle vs. Time** to the appropriate function. Include a copy of the graph with the fit here.
Graph:

What is the angular acceleration found from the fit? What object is accelerating at this rate?
A:

How is the motion of the falling mass related to the motion of the wheel in the rotary motion sensor?
A:

If you look at the Logger Pro file, on page 2 you will see two columns: "PE" is the gravitational potential energy of the 1-kg mass as it drops; "KE" is the translational kinetic energy of the falling mass. **Add new column called "PE+KE" and make a plot of "PE+KE" vs. Time**. Include a copy of the graph here.
Graph:

From the graph: what is the total energy of system before the 1-kg mass is dropped?
A:

Does the total energy of the 1-kg mass and the wheel of the rotary motion sensor change? Does it increase or decrease? Where does the energy go to or come from?
A:

Add new column called "I", moment of inertia, and use your result from pre-lab as a guide to calculate your moment of inertia. **Plot I vs. Time and copy the graph here**.
Graph:

There will be lots of noise at the beginning and at the end of the run. This comes from tiny variations being amplified by numerical calculations. In the middle portion of the run you will see that "I" is roughly constant**. Does this make sense? Why or why not?**
A:

What is the value of your moment of inertia (with uncertainty)? (If you don't know how to do this, see the supplemental file.)
A:

Repeat the calculations for the person holding a 1-kg mass on each arm and **arms stretched out**. **What is the moment of inertia in this configuration (with uncertainty)?**
A:

Is it larger than, smaller than or the same as the moment of inertia when the weights were held close to the body? Does this make sense? Why or why not?
A:

Using the time it takes for you to go two full revolutions, calculate the angular velocity when you are sitting on the stool, holding a 1-kg mass in each hand, with your arms **stretched to the sides**. **What is this angular velocity (with uncertainty)?**
A:

Use your expression from the warm up and your measured moment of inertia to **predict the angular velocity** you should have when you move your arms in and hold the two 1-kg masses close to your body. **What is this prediction (with uncertainty)?**
A:

Using the time it takes for you to go two full revolutions, calculate the angular velocity when you are sitting on the stool, holding a 1-kg mass in each hand, with your arms **close to your body**. **What is this angular velocity (with uncertainty)?**
A:

Does your prediction match your measurement? Don't forget the role of uncertainty!
A:

Part 2: Gyroscopes (40 minutes)
In this part of the lab, you will explore gyroscopes and the phenomenon of precession.

First, hold a bicycle wheel that is not rotating from one handle, such that the wheel is vertical and the handle is horizontal. **Describe what you have to do in order to tilt the wheel upwards**.
A:

What do you think will happen if the bicycle wheel were spinning?
A:

Now spin the wheel as fast as you can and hold it from one handle, such that the wheel is vertical and the handle is horizontal. **Describe what happens when you try to tilt the wheel upwards**. Everyone should try it out – you really need to feel it to believe it.
A:

Can you explain why the spinning wheel behaves as it does when you try to tilt it upwards? (*Hint*: Think about angular momentum and torque.) Discuss with your TF.
A:

Put a string through the handle. Hold the string vertical and the wheel vertical, then let go of the wheel. **What happens if the wheel is not rotating?**
A:

Describe what happens if the wheel is rotating.
A:

What happens if the wheel is rotating in the other direction?
A:

For the rest of the lab you will be using a gyroscope. Get a gyroscope from your TF. **IMPORTANT: Be very careful with the gyroscope. When you are finished, put the gyroscope back in the wooden box. If you drop it on the floor, it will be damaged, and you will have to exchange the ball bearings!**

The gyroscope comes with a gimbal mount. This mount allows the gyroscope to freely rotate along two axes of rotation (horizontal and vertical). First, you will explore the behavior of the gyroscope without the extra rod, as shown in the picture in the materials section. For additional information on how to set up the gyroscope, consult the supplemental material.

Spin the gyroscope with the motor and place it on the mount. With the rotating disk horizontal, touch the c-shaped gimbal and try rotating it around the vertical axis. **What happens? What do you think should happen?**

A:

Now tilt the gyroscope so that the disk is not rotating horizontally. Touch the edge of the c-shape gimbal and try rotating it around the vertical axis. **What happens? Can you explain what happens based on adding angular momentum vectors?** (Hint: remember trying to tilt the bicycle wheel upwards.)
A:

Wait for the gyroscope to stop spinning (this might take a minute or two). Spin it up again to maximum speed using the motor, and place it on the mount. Attach the long rod as described in the supplemental, and orient the gyroscope such that the rod is neither vertical nor horizontal. Now the gyroscope is clearly out of balance. Via the lever arm, gravity will cause a torque. This torque sets the gyroscope into a rotation around the vertical axis, called precession. **How can you change the orientation of the gyroscope (the angle the rod makes with the vertical) without pushing/pulling too hard on the rod?**
A:

Change the orientation of the gyroscope a little bit and watch what happens to the precession speed. Change the orientation a few more times, observing what happens to the precession speed after each orientation change. **Does the precession speed depend on the gyroscope orientation?**
A:

What do you think would happen if you attach a weight to the end of the lever arm? Why?
A:

VI. Conclusion

(BONUS) Why does a spinning top not fall over?
A:

Please fill out the following survey before leaving today. Thanks!

https://harvard.qualtrics.com/SE/?SID=SV_3JfhBWj4MYg63w9

What is the most important thing you learned in lab today?
A: