Lab x: Bicycle Wheels

Pre-lab: In today's lab, we will be exploring some properties of bicycle wheels. We will experiment with two different sizes of "double" bicycle wheels and work to relate our experiences to physics concepts important for rotational motion. **For this lab, write your responses to questions on the paper provided, and not in your lab notebook.** You may keep additional notes in your notebook if you wish, but **the work you submit on the worksheets will be reviewed in place of your lab notebook for this lab**.

Prelude to Act 1: As a setup to the experiment, consider the scenario below.

You are blindfolded and you hold a single bicycle wheel in front of you with your arms outstretched, and with one hand on each side of its axle. You rotate the axle of the wheel by 90° and then back again. Do you think you could tell the difference between a wheel that is spinning and one that is not (simply by the feel of the wheel)? Why or why not? Think about this on your own for a minute or two, and write down a few sentences below in response. (This sheet will be collected before we begin the main part of the lab. Your work will be graded on your thoughtful consideration of the scenario, and not on the correctness of your answer.)

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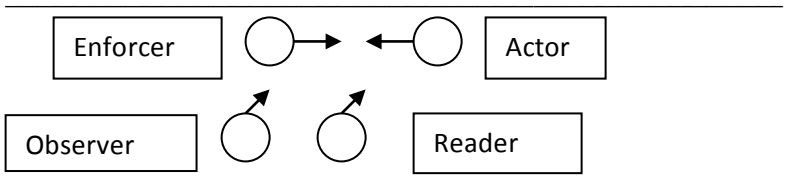
Roles: For this lab, you will be assigned roles which differ slightly from the usual. You should find your name and assigned roles written on a nametag. You will also find an ID number that you will use later.

Introduction: You will be experimenting with the two double bicycle wheel systems that are at your table. You will have two opportunities (Acts 1 & 2) to conduct each of four different experiments where you will systematically vary different parameters of these systems. The experiments are designed to demonstrate what effect the changes have when the axle of wheels is repeatedly tilted by 90° and then returned to its original orientation. This is a carefully scripted experiment, and is very different from what we've done in our previous lab sessions.

Keep in mind: The important physics quantities in this experiment are moment of inertia (I), angular velocity ($\vec{\omega}$), and a new quantity called angular momentum ($\vec{L}$), which is defined as $\vec{L} = I\vec{\omega}$. Angular momentum is a vector quantity. For each of our bicycle wheels, the direction of the angular momentum vector ($\vec{L}$) is given by the right hand rule, and always points along the axle of the wheel. When you tilt the axle of the wheel, you are changing the direction of the angular momentum vector.

Setup: Each group member will take on his/her initial role, and stand as shown in the figure below. To help with this arrangement, your group's approximate positions are marked in tape on the lab floor. The Actor stands with his/her right shoulder to the wall, holding the wheels out at shoulder height such that the laser pointer starts on the tape line on the wall. The Enforcer faces the Actor.



Responsibilities for each role: During this lab you will be playing *one* role at a time (and two roles total). It is particularly important that you stick to the roles today. Next week, we will begin the lab session by discussing today's experiments from the perspective of the different roles, and you will have the opportunity then to try out the other roles as we discuss what you have learned.

The **Reader** will read the description of each scenario aloud. S/he will count the number of times the Actor tilts the axle of the wheels for each trial, and say 'stop' when they have completed 7 tilts. S/he will check off each trial as it is completed.

The **Enforcer** will set the wheels in motion (or not) at the start of each trial as described by the Reader, and make sure the Actor tilts the axle of the wheels as described. S/he will spin the wheels at a consistently fast rate, as demonstrated by the instructor. The spin speed will only differ for trials near the beginning where you are asked to spin the wheels at a slower speed.

The **Actor** will tilt the axle of the wheels from horizontal to vertical (a full 90°) to horizontal (another full 90°) at an appropriate and consistent speed, with the goal of moving the laser pointer as closely as possible along the vertical tape on the wall. The tilt speed will be demonstrated before we begin the trials, and will differ only for trials near the end of the experiment, where you will be asked to tilt the axle of the wheels at a (painfully) slow speed. The actor will focus also on the amount of resistance s/he feels (or the amount of effort it takes to keep the laser pointer lined up) from trial to trial.

The **Observer** will watch closely, paying particular attention to how the movement of the laser changes from trial to trial. This will give an indication of the resistance that the Actor is feeling from trial to trial. In addition, s/he will make sure the laser pointer begins on the tape line at the start of each trial.

Act 1: Work through the four experiments below, exactly as described. Think of this as a scientific investigation of a specific problem. As you work through each experiment, notice that you are changing one variable (thing) at a time from trial to trial. One trial acts as a reference to another, and the sets of trials in an experiment are repeated to reinforce or confirm the experience and observation. One trial, where neither wheel is spinning, is repeated often in all four experiments. This acts as a control trial, or a trial where none of the variables are changed, and in this way it can act as a reference that can be compared to all of the other types of trials. As an Actor or Observer, try to stay focused and to collect data for yourself, either through experience or observation. Similarly, the Enforcer and Reader have the responsibility to make the experiment run smoothly and correctly.

Act 1 – Experiment 1: How is the spin speed of the wheels related to the total angular momentum of the bicycle wheels?

Use the set of big wheels for all of Experiment 1.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐1 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, you will **tilt the axle at a quick pace** (which you will keep consistent for the next several trials).

☐2 Next, **one wheel will spin at a slow speed and the other will not spin**. Enforcer, spin just the left wheel (upward from your perspective) at a slow speed. Actor, **tilt the axle at the same quick pace** as before.

☐3 Next, **one wheel will spin at a fast speed and the other will not spin**. Enforcer, spin just the left wheel upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐4 (reference trial) **Neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐5 (same as #2) **One wheel will spin at a slow speed and the other will not spin**. Enforcer, spin just the left wheel upward at a slow speed. Actor, **tilt the axle at the same quick pace** as before.

☐6 (same as #3) **One wheel will spin at a fast speed and the other will not spin**. Enforcer, spin just the left wheel upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

PAUSE here. Once all of the groups have reached this point, the instructor will give a brief demonstration to reiterate the appropriate tilt and spin speeds. The instructor will then ask everyone to move on to Experiment 2 together.

Act 1 - Experiment 2: How is the size of the wheels related to the total angular momentum of the bicycle wheels?

Begin with the set of small wheels.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐7 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐8 **Both small wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

Switch to the set of big wheels.

☐9 This time **both large wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐10 (reference trial) **Neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐11 (same as #9)This time **both large wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

Switch back to the set of small wheels.

☐12 (same as #8)**Both small wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

PAUSE here. Once all of the groups have reached this point, the instructor will give a brief demonstration to reiterate the appropriate tilt and spin speeds. The instructor will then ask everyone to move on to Experiment 3 together.

Act 1 - Experiment 3: How is the spin direction of the wheels related to the total angular momentum of the bicycle wheels?

Use the set of large wheels for all of Experiment 3.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐13 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐14 **Both wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐15 This time **the wheels will spin in opposite directions from one another, both at a fast speed**. Enforcer, spin the left wheel upward at a fast speed and the right wheel downward at the same fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐16 (reference trial) **Neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐17 (same as #14) This time **both wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐18 (same as #15) This time **the wheels will spin in opposite directions from one another, both at a fast speed**. Enforcer, spin the left wheel upward at a fast speed and the right wheel downward at the same fast speed. Actor, **tilt the axle at the same quick pace** as before.

PAUSE here. Once all of the groups have reached this point, the instructor will demonstrate the difference between fast and slow tilting of the axle, as required for Experiment 4. The instructor will then ask everyone to move on to Experiment 4 together.

Act 1 - Experiment 4: How is the tilt speed of the axle related to the amount of resistance or deflection of the bicycle wheels?

Use the set of small wheels for all of Experiment 4.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐19 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the small wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐20 This time **both small wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐21 This time **both small wheels will spin in the same direction at a fast speed**, but the tilt rate will be much slower. Enforcer, spin both wheels upward at a fast speed. Actor, this time you should **tilt the axle at a (painfully) slow rate**.

☐22 **Neither wheel will spin**, and the tilt rate will be slow. Enforcer, make sure the small wheels are not spinning. Actor, **tilt the axle at the same (painfully) slow rate** as before.

☐23 (same as #21) This time **both small wheels will spin in the same direction at a fast speed**, and the tilt rate will be slow. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same (painfully) slow rate** as before.

☐24 (same as #20) This time **both small wheels will spin in the same direction at a fast speed**, and the tilt rate will be quick. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

Intermission 1: You will be given a page of questions to answer.

Lab x: Bicycle Wheels – Intermission 1

General Instructions: We would like you to take a moment to record some of your observations from Act 1. The following questions are intended to help you organize your ideas about each of the four experiments. This sheet will be collected before we begin Act 2. Your work will be returned next week, when we will have a group discussion about this lab.

How did the four experiments provide information about angular momentum? You were using torque as a tool to study properties of the angular momentum of the bicycle wheel system. Depending on your role, the difficulty in keeping the laser pointer aligned to the tape, the resistance felt in tilting the axle of the wheels, or the amount the laser pointer was deflected away from the tape were all indications of a torque on or by the system of bicycle wheels. And that torque is directly related to the way the angular momentum of the wheels changes as the axle of the wheels is tilted.

Physics Context: We have seen torque defined in two different ways in class: (i) $\tau = rF\sin(\phi)$, where F is the force applied to an object, r is the distance from the axis of rotation to the applied force, and ϕ is the angle between F and the line that defines r; and (ii) $\tau = I\alpha$, where I is the moment of inertia of an object. Remember that α is the angular acceleration of the rotating object, and $\alpha = \dfrac{\Delta\omega}{\Delta t}$, the time rate of change of the angular velocity.

Torque can also be expressed in terms of the new quantity of angular momentum, where

$$\vec{\tau} = \frac{\Delta\vec{L}}{\Delta t},$$

or the time rate of change of angular momentum. This new relationship between torque and the time rate of change in angular momentum allows us to use torque as a tool to investigate (properties of) the total angular momentum of the dual bicycle wheel system in today's experiments. Don't forget that angular momentum is defined as

$$\vec{L} = I\vec{\omega},$$

where I is the moment of inertia of a spinning object, and $\vec{\omega}$ is the object's angular velocity. We have not explicitly used the vector nature of torque previously, but it is true that torque ($\vec{\tau}$) and angular momentum ($\vec{L}$) are both *vector quantities*, meaning that they have a magnitude (size) and a direction associated with them. In our experiment, the direction of the angular momentum vector ($\vec{L}$) is given by the right hand rule, and always points along the axle of the wheel. When you tilt the axle of the wheel, you are changing the direction of the angular momentum vector.

The following questions are meant to help you pull these ideas together. Begin by considering what physics quantities were varied in the experiments your group did:

1. Which role did you play during Act 1? (circle one)

Reader Actor Enforcer Observer

2. a) What physics quantity was varied Experiment 1, when we changed the spin speed of the bicycle wheels? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on the definition of (equation for) angular momentum, how did varying the spin speed affect the total angular momentum of the bicycle wheels? Briefly justify your answer.

3. a) What physics quantity was varied in Experiment 2, when we changed the size of the bicycle wheels? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on the definition of (equation for) angular momentum, how did varying the size affect the total angular momentum of the bicycle wheels? Briefly justify your answer.

4. a) What physics quantity was varied in Experiment 3, when we changed the directions that the bicycle wheels were spinning? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on the definition of (equation for) angular momentum, how did varying the directions affect the total angular momentum of the bicycle wheels? Briefly justify your answer.

5. a) What physics quantity was varied in Experiment 4, when we changed the tilt speed of the axle? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on our new definition of (equation for) torque, how did varying the tilt speed of the axle affect the torque associated with the bicycle wheels? Briefly justify your answer.

6. In general, over a single trial the magnitude of the angular momentum remained constant; but if $\vec{\tau} = \frac{\Delta \vec{L}}{\Delta t}$, how is it that the bicycle wheels produced a torque over a single trial?

7. How is torque related to what you felt as an Actor or observed in an Observer, Reader, or Enforcer role? In other words, what was it that you felt as an Actor, or saw in an observing role that you can associate with the physics concept of torque?

These questions will be collected before moving on to Act 2, during which you will change roles and repeat the four experiments. As you repeat the experiments during Act 2, try to think about which physical quantities are changing. You will work through a set of similar questions during Intermission 2. You will not be graded on the consistency of your answers between Act 1 and Act 2. If your answer to a question changes, that is fine – your answers should always reflect your current thinking.

Act 2: You will now take on your new Role (check your nametag). Work through the four experiments below, exactly as described. Again, think of this as a scientific investigation of a specific problem. As you work through each experiment, notice that you are changing one variable (thing) at a time from trial to trial. One trial acts as a reference to another, and the sets of trials in an experiment are repeated to reinforce or confirm the experience and observation. One trial, where neither wheels is spinning, is repeated often in all four experiments. This acts as a control trial, or a trial where none of the variables are changed, and in this way it can act as a reference that can be compare all of the other types of trials. As an Actor or Observer, try to stay focused and to collect data for yourself, either through experience or observation. Similarly, the Enforcer and Reader have the responsibility to make the experiment run smoothly and correctly.

Act 2 – Experiment 1: How is the spin speed of the wheels related to the total angular momentum of the bicycle wheels?

Use the set of big wheels for all of Experiment 1.

> Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐1 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, you will **tilt the axle at a quick pace** (which you will keep consistent for the next several trials).

☐2 Next, **one wheel will spin at a slow speed and the other will not spin**. Enforcer, spin just the left wheel (upward from your perspective) at a slow speed. Actor, **tilt the axle at the same quick pace** as before.

☐3 Next, **one wheel will spin at a fast speed and the other will not spin**. Enforcer, spin just the left wheel upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐4 (reference trial) **Neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐5 (same as #2) **One wheel will spin at a slow speed and the other will not spin**. Enforcer, spin just the left wheel upward at a slow speed. Actor, **tilt the axle at the same quick pace** as before.

☐6 (same as #3) **One wheel will spin at a fast speed and the other will not spin**. Enforcer, spin just the left wheel upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

PAUSE here. Once all of the groups have reached this point, the instructor will give a brief demonstration to reiterate the appropriate tilt and spin speeds. The instructor will then ask everyone to move on to Experiment 2 together.

Act 2 - Experiment 2: How is the size of the wheels related to the total angular momentum of the bicycle wheels?

Begin with the set of small wheels.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐7 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐8 **Both small wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

Switch to the set of big wheels.

☐9 This time **both large wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐10 (reference trial) **Neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐11 (same as #9)This time **both large wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

Switch back to the set of small wheels.

☐12 (same as #8)**Both small wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

PAUSE here. Once all of the groups have reached this point, the instructor will give a brief demonstration to reiterate the appropriate tilt and spin speeds. The instructor will then ask everyone to move on to Experiment 3 together.

Act 2 - Experiment 3: How is the spin direction of the wheels related to the total angular momentum of the bicycle wheels?

Use the set of large wheels for all of Experiment 3.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐13 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐14 **Both wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐15 This time **the wheels will spin in opposite directions from one another, both at a fast speed**. Enforcer, spin the left wheel upward at a fast speed and the right wheel downward at the same fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐16 (reference trial) **Neither wheel will spin**. Enforcer, make sure the wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐17 (same as #14) This time **both wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐18 (same as #15) This time **the wheels will spin in opposite directions from one another, both at a fast speed**. Enforcer, spin the left wheel upward at a fast speed and the right wheel downward at the same fast speed. Actor, **tilt the axle at the same quick pace** as before.

PAUSE here. Once all of the groups have reached this point, the instructor will demonstrate the difference between fast and slow tilting of the axle, as required for Experiment 4. The instructor will then ask everyone to move on to Experiment 4 together.

Act 2 - Experiment 4: How is the tilt speed of the axle related to the amount of resistance or deflection of the bicycle wheels?

Use the set of small wheels for all of Experiment 4.

Note: After you complete each trial below, check off the box next to the trial to indicate its completion.

☐19 (reference trial) First, **neither wheel will spin**. Enforcer, make sure the small wheels are not spinning. Actor, **tilt the axle at the same quick pace** as before.

☐20 This time **both small wheels will spin in the same direction at a fast speed**. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

☐21 This time **both small wheels will spin in the same direction at a fast speed**, but the tilt rate will be much slower. Enforcer, spin both wheels upward at a fast speed. Actor, this time you should **tilt the axle at a (painfully) slow rate**.

☐22 **Neither wheel will spin**, and the tilt rate will be slow. Enforcer, make sure the small wheels are not spinning. Actor, **tilt the axle at the same (painfully) slow rate** as before.

☐23 (same as #21) This time **both small wheels will spin in the same direction at a fast speed**, and the tilt rate will be slow. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same (painfully) slow rate** as before.

☐24 (same as #20) This time **both small wheels will spin in the same direction at a fast speed**, and the tilt rate will be quick. Enforcer, spin both wheels upward at a fast speed. Actor, **tilt the axle at the same quick pace** as before.

Intermission 2: You will be given a page of questions to answer.

Lab x: Bicycle Wheels – Intermission 2

General Instructions: We would like you to take a moment to record some of your observations from Act 2. The following questions are intended to help you organize your ideas. This sheet will be collected before we begin Act 3. Your work will be returned next week, when we will have a group discussion about this lab. *Remember:* You will not be graded on the consistency of your answers between Act 1 and Act 2. If your answer to a question changes, that is fine – your answers should reflect your current thinking.

How did the four experiments provide information about angular momentum? You were using torque as a tool to study properties of the angular momentum of the bicycle wheel system. Depending on your role, the difficulty in keeping the laser pointer aligned to the tape, the resistance felt in tilting the axle of the wheels, or the amount the laser pointer was deflected away from the tape were all indications of a torque on or by the system of bicycle wheels. And that torque is directly related to the way the angular momentum of the wheels changes as the axle of the wheels is tilted.

Physics Context: We have seen torque defined in two different ways in class: (i) $\tau = rF\sin(\phi)$, where F is the force applied to an object, r is the distance from the axis of rotation to the applied force, and ϕ is the angle between F and the line that defines r; and (ii) $\tau = I\alpha$, where I is the moment of inertia of an object. Remember that α is the angular acceleration of the rotating object, and $\alpha = \dfrac{\Delta\omega}{\Delta t}$, the time rate of change of the angular velocity.

Torque can also be expressed in terms of the new quantity of angular momentum, where

$$\vec{\tau} = \frac{\Delta \vec{L}}{\Delta t},$$

or the time rate of change of angular momentum. This new relationship between torque and the time rate of change in angular momentum allows us to use torque as a tool to investigate (properties of) the total angular momentum of the dual bicycle wheel system in today's experiments. Don't forget that angular momentum is defined as

$$\vec{L} = I\vec{\omega},$$

where I is the moment of inertia of a spinning object, and $\vec{\omega}$ is the object's angular velocity. We have not explicitly used the vector nature of torque previously, but it is true that torque ($\vec{\tau}$) and angular momentum ($\vec{L}$) are both *vector quantities*, meaning that they have a magnitude (size) and a direction associated with them. In our experiment, the direction of the angular momentum vector ($\vec{L}$) is given by the right hand rule, and always points along the axle of the wheel. When you tilt the axle of the wheel, you are changing the direction of the angular momentum vector.

The following questions are meant to help you pull these ideas together. Begin by considering what physics quantities were varied in the experiments your group did:

1. Which role did you play during Act 2? (circle one)

Reader Actor Enforcer Observer

2. a) What physics quantity was varied Experiment 1, when we changed the spin speed of the bicycle wheels? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on the definition of (equation for) angular momentum, how did varying the spin speed affect the total angular momentum of the bicycle wheels? Briefly justify your answer.

3. a) What physics quantity was varied in Experiment 2, when we changed the size of the bicycle wheels? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on the definition of (equation for) angular momentum, how did varying the size affect the total angular momentum of the bicycle wheels? Briefly justify your answer.

4. a) What physics quantity was varied in Experiment 3, when we changed the directions that the bicycle wheels were spinning? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on the definition of (equation for) angular momentum, how did varying the directions affect the total angular momentum of the bicycle wheels? Briefly justify your answer.

5. a) What physics quantity was varied in Experiment 4, when we changed the tilt speed of the axle? (circle one)

I Δt magnitude of $\vec{\omega}$ direction of $\vec{\omega}$

b) Based on our new definition of (equation for) torque, how did varying the tilt speed of the axle affect the torque associated with the bicycle wheels? Briefly justify your answer.

6. In general, over a single trial the magnitude of the angular momentum remained constant; but if $\vec{\tau} = \frac{\Delta \vec{L}}{\Delta t}$, how is it that the bicycle wheels produced a torque over a single trial?

7. How is torque related to what you felt as an Actor or observed in an Observer, Reader, or Enforcer role? In other words, what was it that you felt as an Actor, or saw in an observing role that you can associate with the physics concept of torque?

These questions will be collected before moving on to Act 3.