The Study of Gyroscopic Motion through Inquiry-Based Learning Activities

Kathryn Bohn, Jeff Georgette, Brian Self, and James Widmann
California Polytechnic State University, San Luis Obispo

Abstract
Students typically struggle with sophomore level dynamics – this difficulty is compounded when the material is extended to three dimensions. To help students gain a physical appreciation for gyroscopic motion, an Inquiry-Based Learning Activity (IBLA) was created. Although most dynamics instructors routinely use a spinning bicycle wheel as a demo, few students get to experience the motion first hand. Similarly, toy gyroscopes can be used to help teach students about precession and demonstrate how gyroscopic navigational devices operate. These hands-on laboratories can be much more powerful than demonstrations and lecturing – the students can actually feel the gyroscopic moments generated. The IBLA was assessed through two problems on the final examination. The first asked what happens to the motion of a gyroscope when you push gently on the outer gimble. The second involved the action-reaction moments involved with gyroscopic motion (e.g., if you are riding your bike and lean to the left, which way to do you have to push on your handlebars). Scores on these different problems along with subjective survey results were used to assess the effectiveness of the IBLA.

Introduction

Due to time constraints and the difficulty of the material, very few universities include three dimensional kinetics and kinematics in their undergraduate curriculum. Cal Poly offers a three- unit dynamics course (on the quarter system) with a subsequent intermediate dynamics class. This intermediate course is a four-unit combined lecture and lab curriculum that facilitates the effectiveness of the hands-on mini-labs and includes significant programming with Matlab. A review of 2D kinematics and kinetics is covered during the first four weeks, including an introduction to computer simulation and numerical techniques. The remainder of the quarter is devoted to three-dimensional motion. During the final week of the course, we cover gyroscopic motion. This is a very difficult concept for most students to grasp, and simple instructor demonstrations don't allow the students to actually feel the gyroscopic moments. To help remedy this situation and hopefully create better conceptual understanding, we created a gyroscopic inquiry-based learning activity.

As a form of active learning, Inquiry-Based Learning Activities (IBLAs) encourage students to actively engage in learning the course material, which is unlike the more passive lecture style typically seen in classrooms. Instead of a professor telling the student's why certain results occurred, the students take charge of their own learning and allow reality to act as the 'authority'. Similar to an experimental procedure, our research had students use the IBLA method to first predict the results of the physical model, then conduct the experiment and finally to complete a worksheet that asks probing questions to test the student's conceptual understanding. Through the hands-on exploration of reality by use of IBLAs, the students will develop conceptual understanding of the intended topics and hopefully break any previous misconceptions. Although most of the research featuring IBLAs is focused on physics, researchers Prince and Vigeant have found evidence that promotes the success of IBLAs in engineering fields. Their research demonstrated the improvement of student's conceptual understanding from the traditional lecture style to the participation in appropriate inquiry-based learning activities[4].

Gyroscope IBLA

The activity was composed of three stations involving precision gyroscopes, a bicycle wheel with handles, and a lazy-susan platform. The first station had students apply a moment to a precision gyroscope by attaching a weight to the outer gimble and observe the resulting precession (Figure 1). The second station had students translate the gyro around the flat table to demonstrate that angular momentum is unchanged in the absence of external moments. They then pushed on the side of the gimbal and observed the precession (similar to one of the final exam questions). On the third station, students held a spinning bicycle wheel by its two handles and yawed about a vertical axis (the spin axis is perpendicular to the outstretched arms). Next, the student held the spinning bicycle wheel by just one handle and rotated it to the side (the spin axis is in the same direction as the outstretched arm). The students also had to apply a roll-moment to the bicycle wheel when standing on a free-spinning turntable, as well as suspend a spinning wheel using a rope attached to its handle.

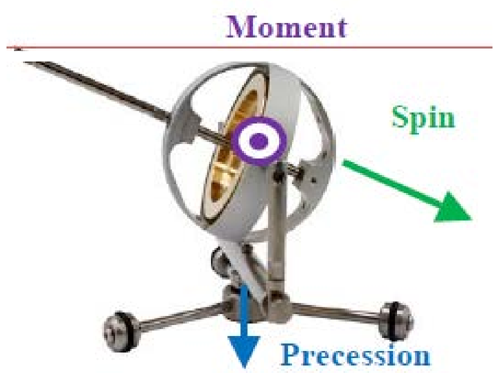


Figure 1. First station figure.

Fig. 2. Students working through station two In Gyroscope IBLA.

Students made predictions (see Appendix A) before running the experiment at each station. Next, they recorded the results on a worksheet (see Appendix B), and responded to the worksheet prompts. Through the inquiry activity, students revisited their predictions and previous ideas after seeing the physical results, and later went on to create informed conclusions. During the hands on activity, the professor and teaching assistants walked around and checked up on student teams to make sure they were doing the activity correctly and helped to answer their questions. The instructors offered additional guidance on how to position the gyroscopes during the activity and how to set up the bicycle wheel on the rope. The concepts that were addressed in this activity were simplified gyroscopic equation (containing moment, precession, and spin) and angular momentum (magnitude and direction). One concept emphasized in the stations was the direction of the applied moment is equal to the cross product of the precession with the spin, where:

$\check{M} = I\overline{\dot{\Phi}} \times \overline{\dot{\Psi}}$, where $\dot{\Phi}$ and $\dot{\Psi}$

are precession and spin, respectively. For example, if the spin axis is as shown in Figure 1, with the moment coming out at you then the cross product of spin with moment yields the precession pointing downwards.

The concepts in this activity, 3D kinetics and kinematics and angular momentum, are important to understand dynamics. Gyroscopic behavior is very non-intuitive and challenging, thus the physical activity allows students to see the precession and spin directions and to physically feel the moments applied to spinning rotors. This activity was done for the Intermediate Dynamics class at Cal Poly for the 2012-2013 year. Teams were comprised of three to four students.

Predictions review

Over the past year we have revised the gyro mini-lab to allow the students more time to discuss the activities in their groups. Originally the activity included four stations, two gyroscopes and two bicycle wheel stations, but in the Spring section the bicycle wheel stations were combined. Students made individual predictions before each stations of the activity; the results are compiled in the table below. The prediction questions and worksheet for the Fall section are found in Appendix A and B. There have been some slight changes to the worksheet over the course of our research as the Spring and Winter quarters had the same tasks to complete, but labeled the stations differently (4a-4b turned into 3c-3d). In Fall, we omitted question b of station 3 and question a of station 4 to shorten the activity and allow for more discussion time.

At station 1 the students were asked to predict how adding a weight on the gyroscope would affect the precession and how changing the weight would change the precession. The students were then asked, in station 2 how translating the gyroscope would affect the spin direction and how an additional force would cause precession. The station 3 prediction questions asked the students to determine the direction the wheel would move when changing its position. This is not intuitive as we are asking them about the resistive forces of the motion. Station 4 asks the students to predict the behavior of the wheel when rotated, again this question deals with the resistive forces from the gyroscopic motion.

Table 1. Prediction correct percentages, winter and spring 2013

Prediction Question	*Station 1a*	*1b*	*Station 2a*	*2b*	*Station 3a*	*3b*	*Station 4*	*4b*
Winter 13 (n = 66)	57%	68%	65%[1]	58%[2]	67%	43%	70%	56%
Spring 13 (n = 59)	71%	83%	70%	81%	68%	48%	44%	58%
Fall 13 (n= 85)	73%	-	74%	-	44%	-	-	63%

[1] Erroneous results due to directions not drawn on figure, fixed for spring '13
[2] Mentioned correct concepts on open ended question

Some of the prediction questions appear to make more sense than others to students as the overall prediction scores at each station show no particular trends. The low prediction scores hint that there is room to better understand the concepts by the end of the class term. Student groups rotated through each station at different times – some performed the precision gyroscope station first, while others performed the bicycle wheel station first. The figure below outlines the progression of student understanding as they move through the stations.

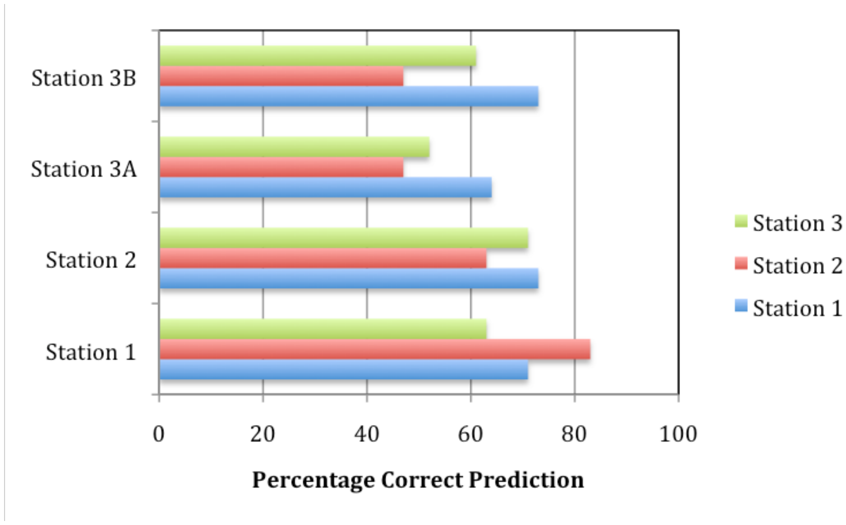


Fig. 4. Percentage of correct responses to prediction sheet questions as the student progressed throughout the stations in the Fall ’13 class

For the most part, the student’s responses improved as they progressed throughout the mini-labs. The students who started at stations 2 and 3 had a larger improvement than those that started at station 1. We noticed a trend of students who struggled with the prediction question for station 3a, which was independent of what station they started at. Overall, the students appear to have gained conceptual understanding of the topic as they progressed through the labs. In some cases the students demonstrated improvement while others have not fully grasped the concepts. When asked how they made their predictions, some students replied that they used principles taught in the class to make an educated guess while others said that they had played with a gyroscope and knew it would behave that way. For future activities, we want to encourage the students to make predictions using conceptual understanding so that by performing the activity reality will act as the teacher and support the conceptual basis.

Worksheet Review

Students filled out worksheets in teams for the activity. The research team noted the common conceptions and misconceptions as follows.

Fall Worksheets Response Themes

On the worksheets, student teams identified fundamental concepts, such as: angular momentum changes when a moment is applied, the simplified gyroscopic equation $\vec{M} = I\overline{\dot{\Phi}} \times \overline{\Psi}$ (Moment = Precession x Spin) (Figure 4), the angular impulse momentum equation $\overline{H_1} + \int \overline{M}\, dt = \overline{H_2}$, and that angular momentum keeps the wheel from falling to horizontal (rope bike-wheel station).

Students wrote different explanations on the worksheet, such as “moment applied causes angular momentum to increase, leads to precession increase.” The correct idea is that the angular momentum magnitude stays constant in these experiments, and thus precession is also constant. Also, the moment causes the direction of the angular momentum vector to change, similar to how a force can cause the direction of linear momentum to change.

Winter Worksheets Response Themes. Besides answering the worksheet questions correctly, students exhibited the following ways of thinking. Their correct concepts included: moment causes a change in angular momentum thus leads to precession; when precession and spin point co-linearly the cross product is zero thus moment is zero; and angular momentum of objects resists changing orientation unless a moment is applied. They did a good job of writing physical experiment results, what they felt and saw from the experiment. Teams did not utilize the conservation of angular momentum equation much and focused more on the simplified gyroscopic equation. On the other hand, their misconceptions included: precession direction is opposite of the change in angular momentum. Similarly to the previous quarter, one misconception was not putting correct directions for moment-spin-precession axes.

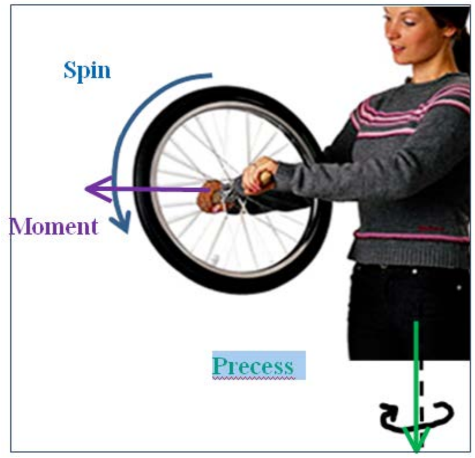


Fig. 5. Precession occurs as person turns to right, they apply counter moment to wheel to keep it in place; station 3a

Spring Worksheets Response Themes. Students observed and explained multiple concepts, such as "moment applied to the disk causes a change in the direction of angular momentum, which causes a precession", and that angular momentum is conserved. On the other hand, misconceptions were listed, such as 'the spin causes the rod to precess because the new angular velocity changes the angular momentum'. The spring worksheet had spin direction drawn on the figure for station 2, which aided the analysis of the cross products. Students explained their thinking in a way that we could see what they were trying to say, by using figures and vectors.

Final Exam/Quiz Question

Around the time of the activity, a homework assignment and quiz were given. The homework and quiz were different for each quarter, but shared the idea of reinforcing and testing the relevant concepts. The homework assignment featured an electric fan with a weight on the end to induce precession (winter '13) or the precession of a top, and the precession of a simplified space station (spring'13). The quiz featured a) a person holding a bicycle wheel pointing outwards, then turning to the left, and b) find the resultant moment when an automobile's tires turn during a right hand turn (spring '13). At the end of the ten-week quarter a final exam problem (see Figure 5) was given to the students to assess their understanding of the gyroscope concepts. The gyroscope at the right (Figure 6) has a spin direction as shown, with angular velocity in the positive x direction. If you push gently on the outer gimbal in the negative x direction (shown as force F), what will happen (be specific)?

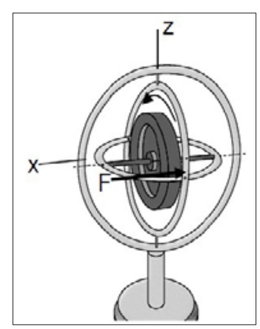


Fig. 6. Final exam question

The grading of the final exam questions follows the format from previous implementations:

- Score of 5 was given if students recognized that the result was a precession of the disk, could apply the correct equation, and compute the axis and the correct direction of the precession.

- Score of 4 was given if students did everything, including finding the correct axis, but gave the wrong direction of precession.
- Score of 3 was given if the students recognized that the result was a precession, wrote the governing equation but then applied it incorrectly.
- Score of 2 was given if the students either recognized precession, or wrote the governing equations but not both.
- Score of 1 was given if student made a basic observation that the force caused a moment, or made some other basic observation.
- Score of 0 was given when the student gave no response or the response showed no understanding of the system.

A second problem, based on a jet engine, (Figure 6) asks students to find the resulting moment acting on the spinning rear-turbine when the aircraft rotates. This problem was modified to the context of a helicopter in motion for the spring quarter '13, and asks the same concept. The assessment scoring is as follows:

- Score of 3 was given if the axis and compensation decisions were both correct
- Score of 2 was given if students found the correct axis, but drew the wrong conclusion on how the pilot should compensate
- Score of 1 was given if students found wrong direction of moment and wrong direction of pilot compensation

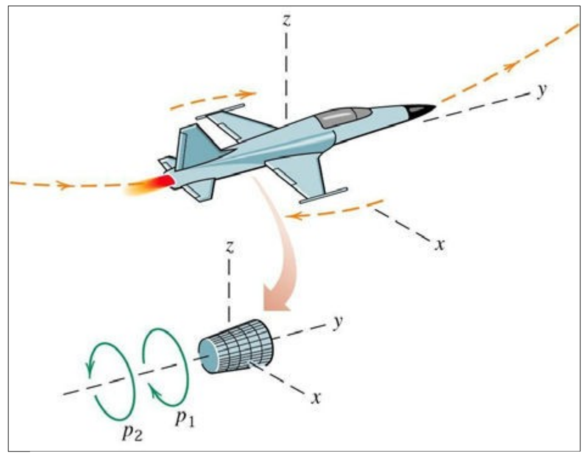


Fig. 7. Final exam question two, rotating turbine in jet. From Meriam and Kraige, 2006

The gyroscope activity taught in the 2012-2013 year is different from the activity in 2007 due to a different instructor and an improved worksheet. The same final exam question was asked for different implementations (albeit slightly different contexts for the helicopter problem). Results from the final exam questions are shown in Table 2.

The scores on the final exam problem indicate improvement on the gimbal problem, but a decrease in performance on the jet turbine/helicopter problem. The change in exam scores from spring 07' to fall '07 was found to be not statistically significant (from the ASEE 2008 paper[5]). From looking at the final problem (helicopter problem in spring'13) most students found the correct direction of the rotor moment. But only a few students figured that the moment on the rotor blades is equal and opposite of the moment acting on the craft body. Some students got the symbols mixed up (spin and procession) or did not put terms into the correct units (which changes the magnitude of the answer). On the final gimbal problem, most students figured out the correct resulting precession direction; we attribute this in part due to the hands on activity.

Table 2. Gyroscope exam question score summary

Class	**Quiz**	**Final Gimbal Problem /5**	**Final Problem Jet turbine/Helicopter /3**
Spring '07 (no lab)	-	3.23	2.1

Fall’07 (mini-lab)	-	3.45	2.26
Winter ’13 IBLA (n = 29)	-	3.48	2.38
Spring ’13 IBLA (n = 69)	6.7/10	4.06	1.9

Subjective Survey

Students provided feedback on the course, the activity, and their experiences in the subjective survey, summarized in the tables below. A Likert scale was used: 1 = strongly disagree to 5 = strongly agree. The activity was reported as motivating and helpful to students.

Table 3. Gyroscope survey summary.

Class	The gyroscope lab was interesting and motivating	…helped me learn about angular momentum and 3d kinetics	You should do the gyro lab in future sections of the course
Winter ‘13	4.1/5	4.0/5	4.3/5
Spring ‘13	4.3/5	4.0/5	4.3/5

The survey also asked when the gyroscope concepts made sense. Each number on the right column states the number of students that realized the concepts made sense for the first time, and understood the concepts afterwards. Through this survey, we found out that 91% (Spring ’13, n = 64) claimed to understand the topic after participating in the activity sequence. The breakdown of the survey results indicates the primary times when the students reported understanding were after the first lecture, during the activity and after the process was over. This can be seen in Table 4.

Some selected responses from students on the survey:

- *“Gyros are really cool and aren't intuitive.”*
- *“Gyroscopic motion confused me the most. Partly because it was at the end of the quarter and everything felt rushed. I always confused the moment and the precession.”*
- *“Gyroscopic motion: It was a difficult concept to grasp because I hadn’t seen anything like it before. Working through the activity definitely helped and it all seemed to click once I saw the bike wheel demonstration.”*

Table 4. When did the concepts make sense? (Spring 2013)

First time understanding concepts	*Percentage of Students*
Beforehand	0%
After first lecture	18
During activity	14
Talking with teammates	5
After activity	15
Discussion in class	5
Studying it later	2
After homework	9
During/after post quiz	23
Still confused	9
Total Class size	(n = 65)

When separately asked on the survey “what topic in the course confused you the most?” the response gyroscopes were mentioned 25% of the time (Spring ’13, n = 64).

Discussion

Overall the hands-on IBLA provided a physical experience with using gyroscopes and bicycle wheels in order to learn the relevant concepts of 3D kinetics and kinematics. Students could feel precession and moments needed to sustain certain spinning motions and witness the non-intuitive nature of precession. Students made sense of the simplified gyroscope equation and were able to apply it to new situations. Students captured the significant concepts of the gyroscope equation and conservation of angular momentum through their worksheet responses. The data from the final exam question suggests slight improvements from using no activity to using the IBLA implementation. The instructor does not do an intervention or explanation for the gyroscope IBLA. Instead, students teach themselves by performing four stations in accordance with the inquiry principles. The subjective survey suggests the activity was helpful and motivating, and should continue in the future as reported by students.

Improvements

The worksheets will be revised with each implementation in a similar fashion to other IBLA activities developed by our team. Perhaps increasing time to complete the activity will be beneficial towards student learning. Some student suggestions for improvement are:

- *“Make the activity itself more about observing what happens with gyroscopes rather than why it happens. Perhaps the explanations on the worksheet could be completed as homework after the activity rather than everyone rushing to complete them.”*
- *“Due to the order of activities and that everyone started at different stations, the questions grew redundant. If there is a way to make it so that the most basic questions/concepts are always answered wherever you start, and then become more involved from there, it would be better for a growth of knowledge.”*

In addition to altering the prediction sheets and worksheets to give the students plenty of time to conduct the experiment and discuss the results, we will be improving our coding method to analyze the responses. We have begun tracking the students’ responses and after a few more iterations of the mini-labs we hope to see a trend in improving student conceptual understanding.Moving forward, we have begun to revise the gyroscope IBLA to further improve the number of students who truly understand the concept, as illustrated by the results of the final exam. To further promote student discussion, we have condensed the activity to two stations for this upcoming quarter. Students will have a longer time to ‘play’ with the gyroscopes and bike wheels. In addition, an intervention will be added to both activities to further guide the students in their conceptual understanding.

Conclusions

Overall, the gyroscope IBLA appears to improve student learning and motivation. Most students appreciated the gyroscope IBLA. Although overall performance on exam problems did not improve greatly between Spring and Fall quarters, there was a substantial increase in those who fully understood the question based on a precision gyroscope. The students also made several suggestions to improve the lab, including having a graduate student present to help explain the labs, linking the lab to additional homework problems, and providing a summary to clarify what was done in the lab. By implementing some of these suggestions, we hope to see even greater improvements in future quarters.

Bibliography

1. Tongue, B. H. and Sheppard, S. D. (2005) Dynamics: Analysis and Design of Systems in Motion, John Wiley & Sons.
2. Meriam, J. L. and Kraige, L.G. (2006) Engineering Mechanics, Volume 2, Dynamics, 6th Edition, John Wiley & Sons.
3. Self, B. P. and Redfield, R. (2001) New Approaches in Teaching Undergraduate Dynamics. Proceedings, American Society for Engineering Education Annual Conference and Exposition.
4. Prince, M. and Vigeant, M. (2006) Using Inquiry-Based Activities to Promote Understanding of Critical Engineering Concepts. Proceedings, American Society for Engineering Education Annual Conference and Exposition.
5. Self, B. P., Birdsong, C. and Rossman, E. (2008) A new spin on teaching 3D kinematics and gyroscopic motion. American Society for Engineering Education Annual Conference and Exposition.

Appendix A: Gyroscopic Prediction Sheet

Anonymous Prediction Sheet S 13
STARTING STATION: STATION 1 → STATION 2 → STATION 3 → BACK TO 1

Before conducting the experiments, please individually record your predictions on this sheet of paper. Your answers will not be graded so do not worry if your predictions are wrong!

Station 1

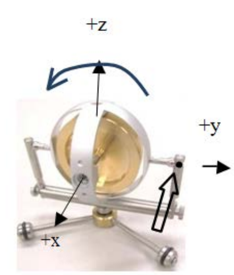
a) When you release the rod, which direction will the gyro precess?

_________________*CW* ____ *CCW* *(view from above)*

b) How does the added weight change the speed of precession?

83.05% Speed up ____*Slow Down* ____*No speed change*

Station 2



a) When tripod base is translated around the table, what direction will the spin axis of the gyro move?

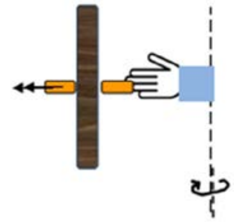
_____Precess +z axis ____Precess +y axis
______Precess +x axis ___ No directional change

b) If you push on the right side of the gimbal as shown, what will happen to the rotor?

Station 3

a) As the wheel spins away from you and you turn your body to the right, what direction will the wheel tilt? (as shown in the figure)

______ *Tilt to your right* ____*Tilt to your Left* ____*No tilt*



b) What direction does the wheel make your arm move?
(see figure for spin directions)

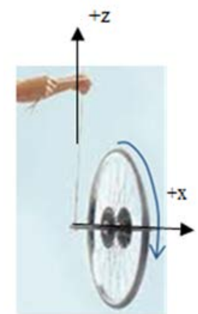
____Up ____ Down (from looking out perspective)
____Left ____ Right ____ No change

Station 4

a) Make a prediction about which direction you will yaw on the platform.

______ Rotate Left Rotate Ri_____ Rotate Left

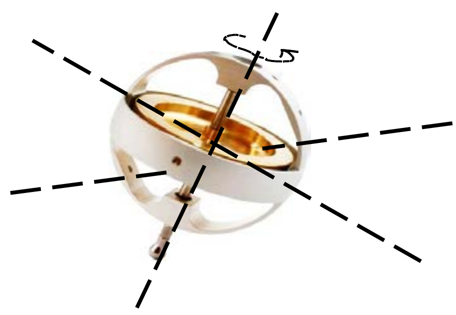
b) Predict the behavior of the wheel when it is supported by a string attached to the outside of the handle (explain your answer)



Appendix B: Gyroscope Worksheet

Gyroscope Mini-Lab (you will turn this in at the end) SPRING 2013

Recall : -- I $\vec{M} = \dot{\vec{\varphi}} \times I\dot{\vec{\psi}}$ and $\dot{\psi}$ are about spin axis, $\dot{\phi}$ denotes precession



Precision Gyroscope (Please do not drop these; they are very expensive)

Please record your predictions on a separate, anonymous sheet.

Station 1

Make your prediction under Station 1(a) on the Prediction Sheet

To spin-up the gyro, connect the electric motor to the top part on the gyro, and turn on the switch on the motor box. Looking at it from the top (where you attach the motor), the rotor will rotate counterclockwise. Make sure to remove the motor from the gyro after spin-up. A short rod is attached to the outer ring; hold the rod in the air at an angle above horizontal and release.

What causes the rod to precess?

Watch the gyro precess. Push up or down gently on rod. *How does the motion change as the rod is moved up and down? Are you surprised by the force necessary to move the rod up or down?*

After the experiment, Sketch a figure with vectors to help explain. Describe in words what is happening with regards to the angular momentum.

Read the next description and Make your prediction under Station 1(b) on the Prediction Sheet. Next, attach the weight to the end of the rod. *How does the added weight change the speed of precession?*

Station 2

Read the description below for the next activity, before doing the activity, and make your prediction under Station 2(a) on the Prediction Sheet.

Let the rotor point at some oblique angle (not vertical or horizontal). While holding the base, slowly slide the system around on the table. (Prediction 2a). After that, slowly lift a base leg off the table surface, no more than 1 inch high. Do this for each leg. (No prediction for lifting a base leg off the table). The orientation of the rotor should point the same direction even if the base moves since there is no moment applied to the rotor (due to the gimbals).

Why does the spin axis remain at the same orientation? If the rotor has constant spin speed, how might a spinning rotor be used to help orient a satellite?

Make a prediction under Station 2(b) on the prediction sheet about the gyro tilt direction from pushing on the right side of the gimbal.

With the rotor spinning in the vertical plane as shown, gently push on one side of the gimbal.

Explain what happens using a figure and the gyroscopic equation.

Station 3

Gyroscopic Bicycle Wheel

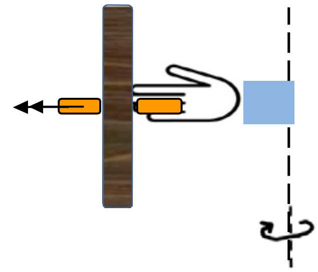
Read the description below for the next activity, and before doing the activity, make your prediction under Station 3(a) on the Prediction Sheet.

Have one person on the team hold the wheel as shown, and a second person push down on the wheel to get it spinning (spin direction on figure). Rotate your body to the right, (clockwise from above), over 360^{o}.

After doing the activity, what do you feel from the handles as you turn your body right? What do you have to do to the wheel to make this motion happen?

Read the description below, and before actually doing the activity, make a prediction under Station 3(b) on the Prediction Sheet.

Hold one of the wheel handles with one hand, so the other handle pointing straight away from you. As you look out from your body/arm, spin the wheel CW. Then rotate your arm and body to the right.



After running the activity, show how and why this happens using a sketch and appropriate equations.

Station 3 Continued

Read the description below, and before actually doing the activity, make a prediction under Station 3(c) on the Prediction Sheet.

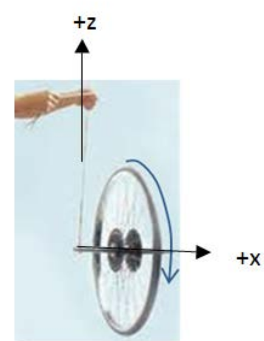
You will need to share one of the rotating platforms with the other bicycle wheel groups, so some of you should start with part d.

c) You will need to get the wheel spinning fairly fast and do the demo right after it starts spinning. Hold the wheel in front of you like shown in the picture. Tilt the bike wheel to the left about 30 degrees (if you did this through a full 90 degrees it would be horizontal).

After doing the exercise, *What happens? Move it back. Describe what and why this happens.*

d) *Read the description below, and before actually doing the activity, make a prediction under Station 3(d) on the Prediction Sheet.*

Lastly, spin the wheel in a vertical plane as fast as you can with the string attached onto a side handle (like the figure at right). Then hold onto the string and watch what happens to the wheel gyroscope.



After running the activity, What happens and why? Explain your answer usinga sketch of the vectors and the simplified gyroscopic equation