LABORATORY VII
ROTATIONAL DYNAMICS

Describing rotations requires applying the physics concepts you have already been studying – position, velocity, acceleration, force, mass, kinetic energy, and momentum to objects that can rotate. However, as we have seen, a modified set of kinematic quantities is sometimes easier to apply to objects with a definite shape – angle, angular velocity, and angular acceleration. To more closely investigate the interactions of these objects, it is also useful to define a modified set of *dynamic* quantities – torque, moment of inertia (or rotational inertia), rotational kinetic energy, and angular momentum.

In this laboratory, you will analyze and predict the motion of extended objects and describe the behavior of structures that are stationary. For static structures, you will apply the concept of torque and the concept of force. To predict motions of objects when torques are applied to them, you will calculate moments of inertia. To compare the motions of objects before and after interactions with each other, you will apply the principle of conservation of energy, including terms for rotational kinetic energy, and you will use a new conservation theory: the conservation of *angular momentum*.

OBJECTIVES:

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

- Use the concept of torque for a system that is in static equilibrium.
- Relate the concepts of torque, angular acceleration and moment of inertia for rigid bodies.
- Use the conservation principles of energy, momentum, and angular momentum for rigid body motion.

PREPARATION:

Read Paul M. Fishbane: Chapter 9, sections 9-2 to 9-6; Chapter 10.

Before coming to lab you should be able to:

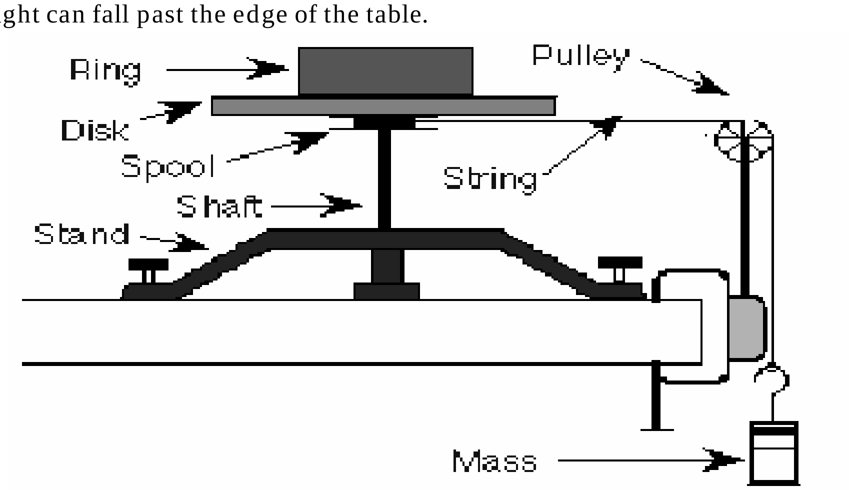
- Determine the net force on an object from its acceleration.
- Know when to use mass and when to use moment of inertia to determine the motion of objects.
- Determine the net torque on an object from its angular acceleration.
- Draw and use force and torque diagrams.
- Explain what is meant by a system in "equilibrium."
- Know how to determine the period of rotation of an object.

PROBLEM #1:
MOMENT OF INERTIA OF A COMPLEX SYSTEM

While examining the engine of your friend's snow blower you notice that the starter cord wraps around a cylindrical ring. This ring is fastened to the top of a heavy, solid disk, "a flywheel," and that disk is attached to a shaft. You are intrigued by this configuration and decide to determine its moment of inertia. Your friend thinks you can add the moment of inertial by parts to get the moment of inertia of the system. To test this idea you decide to build a laboratory model described below to determine the moment of inertia of a similar system from the acceleration of the hanging weight.

EQUIPMENT

For this problem you will have a disk, which is mounted on a sturdy stand by a metal shaft. Below the disk there is a metal spool on the shaft to wind string around. A ring sits on the disk so both ring and disk share the same rotational axis. A length of string is wrapped around the spool and then passes over a pulley lined up with the tangent to the spool. A weight is hung from the other end of the string so that the weight can fall past the edge of the table.



As the hanging weight falls, the string pulls on the spool, causing the ring / disk / shaft / spool system to rotate. You will also have a meter stick, a stopwatch, a pulley clamp, a mass hanger, a mass set and the video analysis equipment in this experiment.

PREDICTION

Restate your friend's idea as an equation.

What quantities will you measure in the lab? What relationships do you need to calculate in order to test your friend's ideas in the lab?

WARM UP

Read: Fishbane Chapter 9. Read carefully Sections 9-3 and 9-4 and Example 9-11.

The following questions will help you figure out the prediction, and find a way to test your friend's idea in the lab. It is helpful to use a problem-solving strategy such as the one outlined below:

1. Draw a side view of the equipment. Draw the velocity and acceleration vectors of the weight. Add the tangential velocity and tangential acceleration vectors of the outer edge of the spool. Also, show the angular acceleration of the spool. What are the relationships among the acceleration of the string, the acceleration of the weight, and the tangential acceleration of the outer edge of the spool if the string is taut?
2. To relate the moment of inertia of the system to the acceleration of the weight, you need to consider a dynamics approach (Newton's second law) especially considering the torques exerted on the system. The relationships between rotational and linear kinematics will also be involved.
3. Draw a free-body diagram for the ring / disk / shaft / spool system. Show the locations of the forces acting on that system. Label all the forces. Does this system accelerate? Is there an angular acceleration? Check to see if you have all the forces on your diagram. Which of these forces can exert a torque on the system? Identify the distance from the axis of rotation to the point where each force is exerted on the system. Write down an equation that gives the torque in terms of the distance and the force that causes it. Write down Newton's second law in its rotational form for this system. Remember that the moment of inertia includes everything in the system that will rotate.
4. Draw a free-body diagram for the hanging weight. Label all the forces acting on it. Does this weight accelerate? Is there an angular acceleration? Check to see if you have included all the forces on your diagram. Write down Newton's second law for the hanging weight. Is the force of the string on the hanging weight equal to the weight of the hanging weight?
5. Can you use Newton's third law to relate pairs of forces shown in different force diagrams?
6. Is there a relationship between the angular acceleration of the ring / disk / shaft / spool system and the acceleration of the hanging weight? To decide, examine the accelerations that you labeled in your drawing of the equipment.
7. Solve your equations for the moment of inertia of the ring / disk / shaft / spool system as a function of the mass of the hanging weight, the acceleration of the hanging weight, and the radius of the spool. Start with the equation containing the quantity you want to know, the moment of inertia of the ring / disk / shaft / spool system. Identify the unknowns in that equation and select equations for each of them from those you have collected. If those equations generate additional unknowns, search your collection for equations that contain them. Continue this process until all unknowns are accounted for. Now solve those equations for your target unknown.
8. For comparison with your experimental results, calculate the moment of inertia of the ring / disk / shaft / spool system using your friend's idea.
9. Use the simulation "Lab7Sim" (See *Appendix F* for a brief explanation of how to use the simulations) to explore the effects of varying the moment of inertia of the system and the mass of

the hanging object. Note that in the simulation, the string acts as if it were attached to the outer edge of the disk. Use the simulation to test your “lab measurement” prediction equation. In making your “lab measurement” prediction, you made several assumptions. Use the parameters in the simulation to (a) think about what some of those assumptions were (for instance, did you notice that you made an assumption about the mass of the pulley?) and (b) test the effects of violating those assumptions.

EXPLORATION

Practice gently spinning the ring / disk / shaft / spool system by hand. How long does it take the disk to stop rotating about its central axis? What is the average angular acceleration caused by this friction? Make sure the angular acceleration you use in your measurements is much larger than the one caused by friction so that it has a negligible effect on your results.

Find the best way to attach the string to the spool. How much string should you wrap around the spool? How should the pulley be adjusted to allow the string to unwind smoothly from the spool and pass over the pulley? Practice releasing the hanging weight and the ring / disk / shaft / spool system.

Determine the best mass to use for the hanging weight. Try a large range. What mass will give you the smoothest motion?

Decide what measurements you need to make to determine the moment of inertia of the system from your Prediction equation. If any major assumptions are involved in connecting your measurements to the acceleration of the weight, decide on the additional measurements that you need to make to justify them.

Outline your measurement plan.

Make some rough measurements to make sure your plan will work.

MEASUREMENT

Follow your measurement plan. What are the uncertainties in your measurements? (See Appendices A and B if you need to review how to determine significant figures and uncertainties.)

Don’t forget to make the additional measurements required to determine the moment of inertia of the ring / disk / shaft / spool system from the sum of the moments of inertia of its components. What is the uncertainty in each of the measurements? What effects do the hole, the ball bearings, the groove, and the holes in the edges of the disk have on its moment of inertia? Explain your reasoning.

ANALYSIS

Determine the acceleration of the hanging weight. How does this acceleration compare to what its acceleration would be if you just dropped the weight without attaching it to the string? Explain whether or not this makes sense.

Using your Prediction equation and your measured acceleration, the radius of the spool and the mass of the hanging weight, calculate the moment of inertia (with uncertainty) of the disk / shaft / spool system.

Adding the moments of inertia of the components of the ring / disk / shaft / spool system, calculate the value (with uncertainty) of the moment of inertia of the system. What fraction of the moment of inertia of the system is due to the shaft? The disk? The ring? Explain whether or not this makes sense.

Compare the values of moment of inertia of the system from these two methods.

CONCLUSION

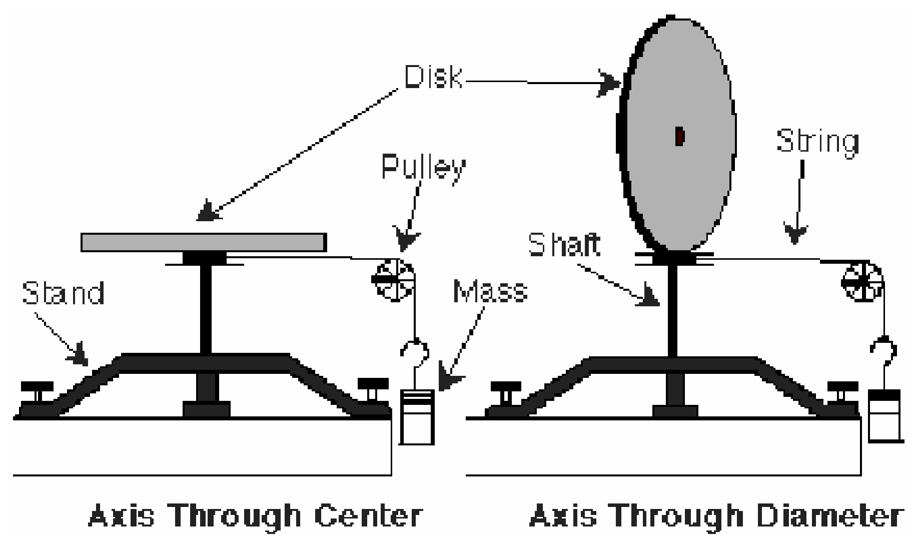
Did your measurements agree with your initial prediction? Why or why not? What are the limitations on the accuracy of your measurements and analysis?

PROBLEM #2:
MOMENTS OF INERTIA ABOUT DIFFERENT AXES

While spinning a coin on a table, you wonder if the coin's moment of inertia spinning on its edge is the same as if it were spinning about an axis through its center and perpendicular to its surface. You do a quick calculation to decide. To test your prediction, you build a laboratory model with a disk that can spin around two different axes, and find the moment of inertia in each configuration by measuring the acceleration of a hanging weight attached to the spinning system by a string.

EQUIPMENT

You will use the same equipment as in Problem #1. A disk is mounted above a spool on a sturdy stand by a metal shaft. The disk can be attached to the shaft so it rotates about its central axis or about its diameter, as shown below.



A length of string is wrapped around the spool and then passes over a pulley lined up with the tangent to the spool. A weight is hung from the other end of the string so that the weight can fall past the edge of the table. As the hanging weight falls, the string pulls on the spool, causing the disk/shaft/spool system to rotate. You will also have a meter stick, a stopwatch, a mass hanger, a mass set, a pulley clamp and the video analysis equipment in this experiment.

PREDICTION

Restate the problem. What are you asked to predict? What relationships do you need to calculate to use the lab model?

WARM UP

Read: Fishbane Chapter 9. Read carefully Sections 9-3 and 9-4 and Examples 9-5, 9-6 and 9-11.

To figure out your prediction, you need to determine how to calculate the rotational inertia of the disk from the quantities you can measure in the laboratory. It is helpful to use a problem solving strategy such as the one outlined below:

More details for answering these Warm up questions are given in Problem #1.

1. Draw a side view of the equipment with all relevant kinematic quantities. Write down any relationships that exist between them. Label all the relevant forces.

2. Determine the basic principles of physics that you will use. Write down your assumptions and check to see if they are reasonable.

3. If you decide to use dynamics, draw a free-body diagram of all the relevant objects. Note the acceleration of the object as a check to see if you have drawn all the forces. Write down Newton's second law for each free-body diagram either in its linear form or its rotational form or both as necessary.

4. Use Newton’s third law to relate the forces between two free-body diagrams. If forces are equal give them the same labels.

5. Identify the target quantity you wish to determine. Use the equations collected in steps 1 and 3 to plan a solution for the target.

6. For comparison with your experimental results, calculate the moment of inertia of the disk in each orientation.

7. Use the simulation “Lab7Sim” (See *Appendix F* for a brief explanation of how to use the simulations) to explore the effects of varying the moment of inertia of the system and the mass of the hanging object. Note that in the simulation, the string acts as if it were attached to the outer edge of the disk. Use the simulation to test your “lab measurement” prediction equation. In making your “lab measurement” prediction, you made several assumptions. Use the parameters in the simulation to (a) think about what some of those assumptions were (for instance, did you notice that you made an assumption about the mass of the pulley?) and (b) test the effects of violating those assumptions.

EXPLORATION

Practice gently spinning the disk / shaft / spool system by hand. How long does it take the disk to stop rotating about its central axis? How long does it take the disk to stop rotating about its diameter? How will friction affect your measurements?

Find the best way to attach the string to the spool. How much string should you wrap around the spool? How much mass will you attach to the other end of the string? How should the pulley be adjusted to allow the string to unwind smoothly from the spool and pass over the pulley? Practice releasing the hanging weight and the disk / shaft / spool system.

Determine the best mass to use for the hanging weight. Try a large range. What mass will give you the smoothest motion?

Decide what measurements you need to make to determine the moment of inertia of the system from your Prediction equation. If any major assumptions are involved in connecting your measurements to the acceleration of the weight, decide on the additional measurements that you need to make to justify them. If you already have this data in your lab journal you don't need to redo it, just copy it.

Outline your measurement plan. Make some rough measurements to make sure your plan will work.

MEASUREMENT

Follow your measurement plan. What are the uncertainties in your measurements? (See Appendices A and B if you need to review how to determine significant figures and uncertainties.)

Don't forget to make the additional measurements required to determine the moment of inertia of the disk / shaft / spool system by adding all of the moments of inertia of its components. What is the uncertainty of each of the measurements? What effects do the hole, the ball bearings, the groove, and the holes in the edges of the disk have on its moment of inertia? Explain your reasoning.

ANALYSIS

Determine the acceleration of the hanging weight. How does this acceleration compare to its acceleration if you just dropped the weight without attaching it to the string? Explain whether or not this makes sense.

Using your Prediction equation and your measured acceleration, the radius of the spool and the mass of the hanging weight, calculate the moment of inertia (with uncertainty) of the disk / shaft / spool system, for both orientations of the disk.

Adding the moments of inertia of the components of the disk / shaft / spool system, calculate the value (with uncertainty) of the moment of inertia of the system, for both orientations of the disk.
Compare the results from these two methods for both orientations of the disk.

CONCLUSION

How do the measured and predicted values of the disk's moment of inertia compare when the disk rotates about its central axis? When the disk rotates around its diameter?

Is the moment of inertia of a coin rotating around its central axis larger than, smaller than, or the same as its moment of inertia when it is rotating around its diameter? State your results in the most general terms supported by the data.

Did your measurements agree with your initial predictions? Why or why not? What are the limitations on the accuracy of your measurements and analysis?

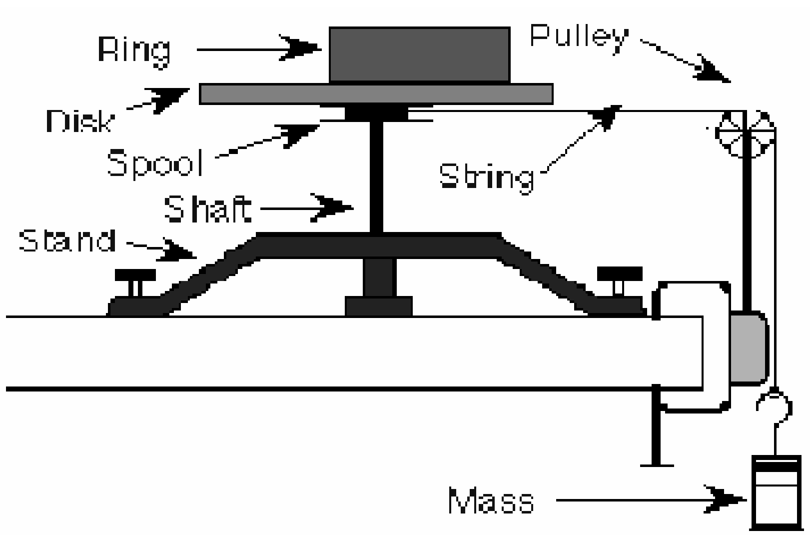
PROBLEM #3:
MOMENT OF INERTIA WITH AN OFF-AXIS RING

You have been hired as a member of a team designing an energy efficient car. The brakes of a traditional car transform the kinetic energy of the car into internal energy of the brake material, resulting in an increased temperature of the brakes. That energy is lost in the sense that it cannot be recovered to power the car. Your task has been to evaluate a new braking system, which transforms the kinetic energy of the car into rotational energy of a flywheel system. The energy of the flywheel can then be used to drive the car. As designed, the flywheel consists of a heavy horizontal disk with an axis of rotation through its center. A metal ring is mounted on the disk but is not centered on the disk. You wonder what effect the off-center ring will have on the motion of the flywheel.

To answer this question, you decide to make a laboratory model to measure the moment of inertia of a ring / disk / shaft / spool system when the ring is off-axis and compare it to the moment of inertia for a system with a ring in the center.

EQUIPMENT

The equipment is the same as Problem #1 and #2.



PREDICTIONS

Restate the problem. What are you asked to predict? What relationships do you need to calculate to use the lab model?

WARM UP

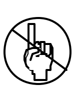
Read: Fishbane Chapter 9. Read carefully Sections 9-3 and 9-4 and Examples 9-7, 9-8 and 9-11.

To figure out your prediction, you need to determine how to calculate the rotational inertia of the disk from the quantities you can measure in this problem. It is helpful to use a problem solving strategy such as the one outlined below:

More details for answering these Warm up questions are given in Problem #1.

1. Draw a side view of the equipment with all the relevant kinematics quantities. Write down any relationships that exist between them. Label all the relevant forces.
2. Determine the basic principles of physics that you will use. Write down your assumptions and check to see if they are reasonable.
3. If you decide to use dynamics, draw a free-body diagram of all the relevant objects. Note the acceleration of the object as a check to see if you have drawn all the forces. Write down Newton's second law for each free-body diagram either in its linear form or its rotational form or both as necessary.
4. Use Newton’s third law to relate the forces between two free-body diagrams. If forces are equal give them the same labels.
5. Identify the target quantity you wish to determine. Use the equations collected in steps 1 and 3 to plan a solution for the target. If there are more unknowns than equations, reexamine the previous steps to see if there is additional information about the situation. If not, see if one of the unknowns will cancel out.
6. For comparison with your experimental results, calculate the moment of inertia of the disk / ring system in each configuration. The parallel-axis theorem should be helpful.

EXPLORATION



THE OFF-AXIS RING IS NOT STABLE BY ITSELF! Be sure to secure the ring to the disk, and be sure that the system is on a stable base.

Practice gently spinning the ring / disk / shaft / spool system by hand. How will friction affect your measurements?

Find the best way to attach the string to the spool. How much string should you wrap around the spool? How much mass will you attach to the other end of the string? How should the pulley be adjusted to allow the string to unwind smoothly from the spool and pass over the pulley? Practice releasing the mass and the ring / disk / shaft / spool system.

Determine the best mass to use for the hanging weight. Try a large range. What mass will give you the smoothest motion?

Decide what measurements you need to make to determine the moment of inertia of the system from your Prediction equation. If any major assumptions are involved in connecting your measurements to the acceleration of the weight, decide on the additional measurements that you need to make to justify them.

Outline your measurement plan. Make some rough measurements to make sure your plan will work.

MEASUREMENT

Follow your measurement plan. What are the uncertainties in your measurements? (See Appendices A and B if you need to review how to determine significant figures and uncertainties.)

Don't forget to make the additional measurements required to determine the moment of inertia of the ring/disk/shaft/spool system from the moments of inertia of its components and the parallel axis theorem. What is the uncertainty in each of the measurements? What effects do the hole, the ball bearings, the groove, and the holes in the edges of the disk have on its moment of inertia? Explain your reasoning.

ANALYSIS

Determine the acceleration of the hanging weight. How does this acceleration compare to its acceleration if you just dropped the weight without attaching it to the string? Explain whether or not this makes sense.

Using your Prediction equation and your measured acceleration, the mass of the hanging weight and the radius of the spool, calculate the moment of inertia (with uncertainty) of the disk/shaft/spool system.

Adding the moments of inertia of the components of the disk/shaft/spool system and applying the parallel axis theorem, calculate the value (with uncertainty) of the moment of inertia of the system.

CONCLUSION

Compare the two values for the moment of inertia of the system *when the ring is off-axis*. Did your measurement agree with your predicted value? Why or why not?

Compare the moments of inertia of the system when the ring is centered on the disk, and when the ring is off-axis.

What effect does the off-center ring have on the moment of inertia of the ring / disk / shaft / spool system? Does the rotational inertia increase, decrease, or stay the same when the ring is moved off-axis?

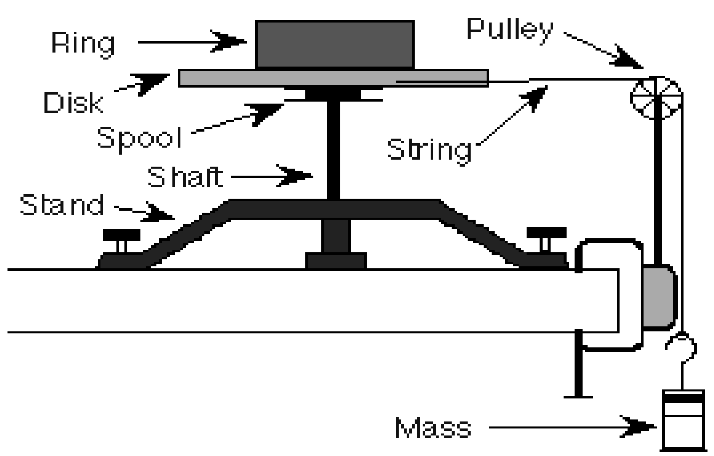
State your result in the most general terms supported by your analysis. Did your measurements agree with your initial prediction? Why or why not? What are the limitations on the accuracy of your measurements and analysis?

PROBLEM #4:
FORCES, TORQUES, AND ENERGY

While examining the manual starter on a snow blower, you wonder why the manufacturer chose to wrap the starter cord around a smaller ring that is fastened to a spool under the flywheel instead of around the flywheel itself. When starting a snow blower, you know you need the starter system to spin as fast as possible when you pull the starter cord. Your friend suggests that the flywheel might spin faster, even if you do the same amount of work when you pull on the handle, if the cord is wrapped around a smaller diameter. You notice that the handle is not very light. To see whether this idea is correct, you decide to calculate the final angular speed of the flywheel after pulling on the handle for a fixed distance with a fixed force, as a function of the spool's radius. To test your calculation, you set up a laboratory model of the flywheel starter assembly. Unfortunately, it is difficult to keep the force on the handle consistent across trials, so in the lab you attach a hanging mass to one end of the cord.

EQUIPMENT

You will use the same equipment as in Problem #1. A length of string can be fastened and wrapped around the ring, the disk or the spool.



As the hanging weight falls, the string causes the ring / disk / shaft / spool system to rotate.

You will also have a stopwatch, a meter stick, a mass hanger, a mass set, a pulley clamp and the video analysis equipment.

PREDICTION

Restate the problem. What quantities do you need to calculate to test your idea?

WARM UP

Read: Fishbane Chapter 9. Read carefully Sections 9-2 and 9-4.

To figure out your prediction, it is useful to use a problem-solving strategy such as the one outlined below:

1. Make two side view drawings of the situation (similar to the diagram in the Equipment section), one just as the hanging mass is released, and one just as the hanging mass reaches the ground (but before it hits). Label all relevant kinematic quantities and write down the relationships that exist between them. What is the relationship between the velocity of the hanging weight and the angular velocity of the ring / disk / shaft / spool system? Label all the relevant forces.

2. Determine the basic principles of physics that you will use and how you will use them. Determine your system. Are any objects from outside your system interacting with your system? Write down your assumptions and check to see if they are reasonable. How will you ensure that your equipment always pulls the cord through the same length when it is wrapped around different diameters?

3. Use dynamics to determine what you must do to the hanging weight to get the force for each diameter around which the cord is wrapped. Draw a free-body diagram of all relevant objects. Note the acceleration of the object in the free-body diagram as a check to see if you have drawn all the forces. Write down Newton's second law for each free-body diagram either in its linear form or its rotational form or both as necessary. Use Newton's third law to relate the forces between two free-body diagrams. If forces are equal, give them the same symbol. Solve your equations for the force that the string exerts.

4. Use the conservation of energy to determine the final angular speed of the rotating objects. Define your system and write the conservation of energy equation for this situation:

What is the energy of the system as the hanging weight is released? What is its energy just before the hanging weight hits the floor? Is any significant energy transferred to or from the system? If so, can you determine it or redefine your system so that there is no transfer? Is any significant energy changed into internal energy of the system? If so, can you determine it or redefine your system so that there is no internal energy change?

5. Identify the target quantity you wish to determine. Use the equations collected in steps 1, 3, and 4 to plan a solution for the target. If there are more unknowns than equations, re-examine the previous steps to see if there is additional information about the situation that can be expressed in an addition equation. If not, see if one of the unknowns will cancel out.

EXPLORATION

Practice gently spinning the ring / disk / shaft / spool system by hand. How will friction affect your measurements?

Find the best way to attach the string to the spool, disk, or ring. How much string should you wrap around each? How should the pulley be adjusted to allow the string to unwind smoothly and pass over the pulley in each case? You may need to reposition the pulley when changing the position where the cord wraps. Practice releasing the weight and the ring / disk / shaft / spool system for each case.

Determine the best mass to use for the hanging weight. Remember this mass will be applied in every case. Try a large range. What mass range will give you the smoothest motion?

Is the time it takes the hanging weight to fall different for the different situations? How will you determine the time taken for it to fall? Determine a good setup for each case (string wrapped around the ring, the disk, or the spool).

Decide what measurements you need to make to check your prediction. If any major assumptions are used in your calculations, decide on the additional measurements that you need to make to justify them. If you already have this data in your lab journal you don't need to redo it, just copy it.

Outline your measurement plan. Make some rough measurements to be sure your plan will work.

MEASUREMENT

Follow your measurement plan. What are the uncertainties in your measurements?

ANALYSIS

Determine the final angular velocity of the ring / disk / shaft / spool system for each case after the weight hits the ground. How is this angular velocity related to the final velocity of the hanging weight? If your calculation incorporates any assumptions, make sure you justify these assumptions based on data that you have analyzed.

CONCLUSION

In each case, how do your measured and predicted values for the final angular velocity of the system compare?

Of the three places you attached the string, which produced the highest final angular velocity? Did your measurements agree with your initial prediction? Why or why not? What are the limitations on the accuracy of your measurements?

Given your results, how much does it matter where the starter cord is attached? Why do you think the manufacturer chose to wrap the cord around the ring? Explain your answers.

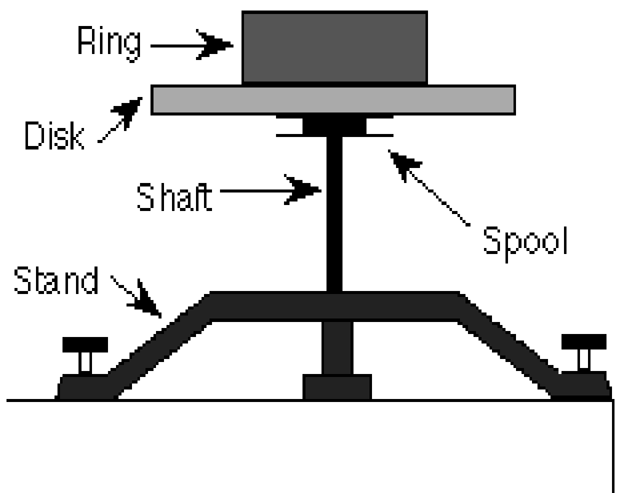
Can you make a qualitative argument, in terms of energy conservation, to support your conclusions?

PROBLEM #5:
CONSERVATION OF ANGULAR MOMENTUM

While driving around the city, your car is constantly shifting gears. You wonder how the gear shifting process works. Your friend tells you that there are gears in the transmission of your car that are rotating about the same axis. When the car shifts, one of these gear assemblies is brought into connection with another one that drives the car's wheels. Thinking about a car starting up, you decide to calculate how the angular speed of a spinning object changes when it is brought into contact with another object at rest. To keep your calculation simple, you decide to use a disk for the initially spinning object and a ring for the object initially at rest. Both objects will be able to rotate freely about the same axis, which is centered on both objects. To test your calculation you decide to build a laboratory model of the situation.

EQUIPMENT

You will use the same basic equipment in the previous problems.



PREDICTION

Restate the problem. What quantities do you need to calculate to test your idea?

WARM UP

Read: Fishbane Chapter 9. Read carefully Sections 9-4 and 9-5 and Examples 9-11 and 9-13.

To figure out your prediction, it is useful to use a problem solving strategy such as the one outlined below:

1. Make two side view drawings of the situation (similar to the diagram in the Equipment section), one just as the ring is released, and one after the ring lands on the disk. Label all relevant kinematic quantities and write down the relationships that exist between them. Label all relevant forces.

2. Determine the basic principles of physics that you will use and how you will use them. Determine your system. Are any objects from outside your system interacting with your system? Write down your assumptions and check to see if they are reasonable.

3. Use conservation of angular momentum to determine the final angular speed of the rotating objects. Why not use conservation of energy or conservation of momentum? Define your system and write the conservation of angular momentum equation for this situation:

Is any significant angular momentum transferred to or from the system? If so, can you determine it or redefine your system so that there is no transfer?

4. Identify the target quantity you wish to determine. Use the equations collected in steps 1 and 3 to plan a solution for the target. If there are more unknowns than equations, reexamine the previous steps to see if there is additional information about the situation that can be expressed in an addition equation. If not, see if one of the unknowns will cancel out.

EXPLORATION

Practice dropping the ring into the groove on the disk as gently as possible to ensure the best data. What happens if the ring is dropped off-center? What happens if the disk does not fall smoothly into the groove? Explain your answers.

Decide what measurements you need to make to check your prediction. If any major assumptions are used in your calculations, decide on the additional measurements that you need to make to justify them.

Outline your measurement plan.

Make some rough measurements to be sure your plan will work.

MEASUREMENTS

Follow your measurement plan. What are the uncertainties in your measurements?

ANALYSIS

Determine the initial and final angular velocity of the disk from the data you collected. Using your prediction equation and your measured initial angular velocity, calculate the final angular velocity of the disk. If your calculation incorporates any assumptions, make sure you justify these assumptions based on data that you have analyzed.

CONCLUSION

Did your measurement of the final angular velocity agree with your calculated value by prediction? Why or why not? What are the limitations on the accuracy of your measurements and analysis?

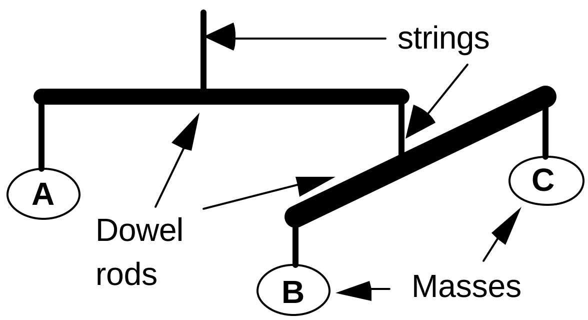
Could you have easily measured enough information to use conservation of energy to predict the final angular velocity of this system? Why or why not? Use your data to check your answer.

PROBLEM #6:
DESIGNING A MOBILE

Your friend has asked you to help make a mobile for her daughter's room. You design a mobile using 5 pieces of string and two rods. The first rod hangs from the ceiling. One object hangs from one end of the rod and another rod hangs from the other end. That second rod has two objects hanging from each end. The project would be easier if your friend's daughter knew what she wanted to hang from the mobile, but she cannot make up her mind. One day it is dinosaurs, another day it is the Power Rangers, and another day it is famous women scientists. Frustrated, you decide to build a laboratory model to test the type of mobile you will build in order to make sure no matter what she decides to hang, the mobile can be easily assembled.

EQUIPMENT

To test your mobile design, you will have two wooden dowel rods, some string, and three objects (A, B, and C) of different masses. Your final mobile should use all these parts.



One metal rod and one table clamp will be used to hang the mobile. You will also have three mass hangers and one mass set.

PREDICTION

Restate the problem. What quantities do you need to calculate to test your design? What are the variables in the system?

WARM UP

Read: Fishbane Chapter 10. Read carefully Sections 10-2 and 10-3 and Examples 10-5 and 10-6.

To figure out your prediction, it is useful to use a problem solving strategy such as the one outlined below:

1. Draw a mobile similar to the one in the Equipment section. Select your coordinate system. Identify and label the masses and lengths relevant to this problem. Draw and label all the relevant forces.

2. Draw a free-body diagram for each rod showing the location of the forces acting on the rods. Label these forces. Identify any forces related by Newton's third law. Choose the axis of rotation for each rod. Identify any torques on each rod.

3. For each free-body diagram, write the equation expressing Newton's second law for forces and another equation for torques. (Remember that your system is in equilibrium.) What are the total torque and the sum of forces on an object when it is in equilibrium?

4. Identify the target quantities you wish to determine. Use the equations collected in step 3 to plan a solution for the target. If there are more unknowns than equations, reexamine the previous steps to see if there is additional information about the situation that can be expressed in an additional equation. If not, see if one of the unknowns will cancel out.

EXPLORATION

Collect the necessary parts of your mobile. Find a convenient place to hang it.

Decide on the easiest way to determine the position of the center of mass of each rod.

Will the length of the strings for the hanging objects affect the balance of the mobile? Why or why not? Try it.

Where does the heaviest object go? The lightest?

Decide what measurements you need to make to check your prediction. If any major assumptions are used in your calculations, decide on the additional measurements that you need to make to justify them.

Outline your measurement plan.

MEASUREMENT

Measure and record the location of the center of mass of each rod. Determine the location on the top rod from which you will hang it. Determine the location on the second rod from which you will hang it. Also, measure and record the mass of each rod and the mass of the three hanging objects.

Is there another configuration of the three objects that also results in a stable mobile?

ANALYSIS

Using the values you measured and your prediction equations, calculate the locations (with uncertainties) of the two strings holding up the rods.

To test your prediction, build your mobile and then hang it. If your mobile did not balance, adjust the strings attached to the rods until it does balance and determine their new positions.

Is there another configuration of the three objects that also results in a stable mobile? Try it.

CONCLUSION

Did your mobile balance as designed? What corrections did you need to make to get it to balance? Were these corrections a result of some systematic error, or was there a mistake in your prediction?

Explain why the lengths of each string were or were not important in the mobile design.

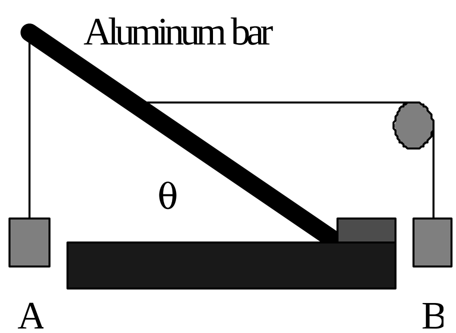
PROBLEM #7:
EQUILIBRIUM

You have been hired to design new port facilities for Duluth. Your assignment is to evaluate a new crane for lifting containers from the hold of a ship. The crane is a boom (a steel bar of uniform thickness) with one end attached to the ground by a hinge that allows it to rotate in the vertical plane. Near the other end of the boom is a motor driven cable that lifts a container straight up at a constant speed. The boom is supported at an angle by another cable. One end of the support cable is attached to the boom and the other end goes over a pulley. That other end is attached to a counterweight that hangs straight down. The pulley is supported by a mechanism that adjusts its height so the support cable is always horizontal. Your task is to determine how the angle of the boom from the horizontal changes, as a function of the weight of the container being lifted. The mass of the boom, the mass of the counterweight, the attachment point of the support cable and the attachment point of the lifting cable have all been specified by the engineers.

You will test your calculations with a laboratory model of the crane.

EQUIPMENT

You will have a channel of aluminum, a pulley, a pulley clamp, two mass hangers, a mass set and some strings.



PREDICTION

Restate the problem. What quantities do you need to calculate to test your design? What parameters are set, and which one(s) will you vary?

WARM UP

Read: Fishbane Chapter 10. Read carefully Sections 10-2 and 10-3 and Examples 10-5 and 10-6.

To figure out your prediction, it is useful to use a problem solving strategy such as the one outlined below:

1. Draw a crane similar to the one in the Equipment section. Select your coordinate system. Identify and label the masses and lengths relevant to this problem. Draw and label all the relevant forces.

2. Draw a free-body diagram for the bar showing the location of the forces acting on it. Label these forces. Choose the axis of rotation. Identify any torques on the rod.

3. Write the equation expressing Newton's second law for forces and another equation for torques. Remember that the bar is in equilibrium.

4. Identify the target quantities you wish to determine. Use the equations collected in step 3 to plan a solution for the target. If there are more unknowns than equations, reexamine the previous steps to see if there is additional information about the situation that can be expressed in an additional equation. If not, see if one of the unknowns will cancel out.

5. Make a graph of the bar's angle as a function of the weight of object A.

EXPLORATION

Collect the necessary parts of your crane. Find a convenient place to build it.

Decide on the easiest way to determine where the center of mass is located on the bar.

Determine where to attach the lifting cable and the support cable so that the crane is in equilibrium for the weights you want to hang. Try several possibilities. If your crane tends to lean to one side or the other, try putting a vertical rod near the end of the crane to keep your crane from moving in that direction. If you do this, what effect will this vertical rod have on your calculations?

Do you think that the length of the strings for the hanging weights will affect the balance of the crane? Why or why not?

Outline your measurement plan.

MEASUREMENT

Build your crane.

Make all necessary measurements of the configuration. Every time only change the mass of object A and determine the angle of the bar when the system is in equilibrium. Remember to adjust the height of the pulley to keep the support string horizontal that hangs the object B for each case.

Is there another configuration of the three objects that also results in a stable configuration?

ANALYSIS

Make a graph of the bar's angle as a function of the weight of object A and compare it with your predicted graph.

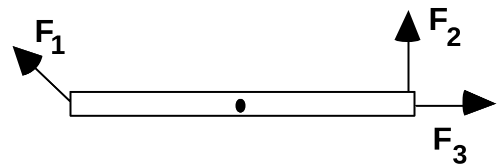
What happens to that graph if you change the mass of object B or the position of the attachment of the support cable to the bar?

CONCLUSION

Did your crane balance as designed? What corrections did you need to make to get it to balance? Were these corrections a result of some systematic error, or was there a mistake in your prediction? In your opinion, what is the best way to construct a crane that will allow you to quickly adjust the setup so as to meet the demands of carrying various loads? Justify your answer.

☑ CHECK YOUR UNDERSTANDING

1. A long stick is supported at its center and is acted on by three forces of *equal* magnitude, as shown at right. The stick is free to swing about its support. $\mathbf{F_2}$ is a vertical force and $\mathbf{F_3}$ is horizontal.



   a. Rank the magnitudes of the torques exerted by the three forces about an axis perpendicular to the drawing at the *left* end of the stick. Explain your reasoning.

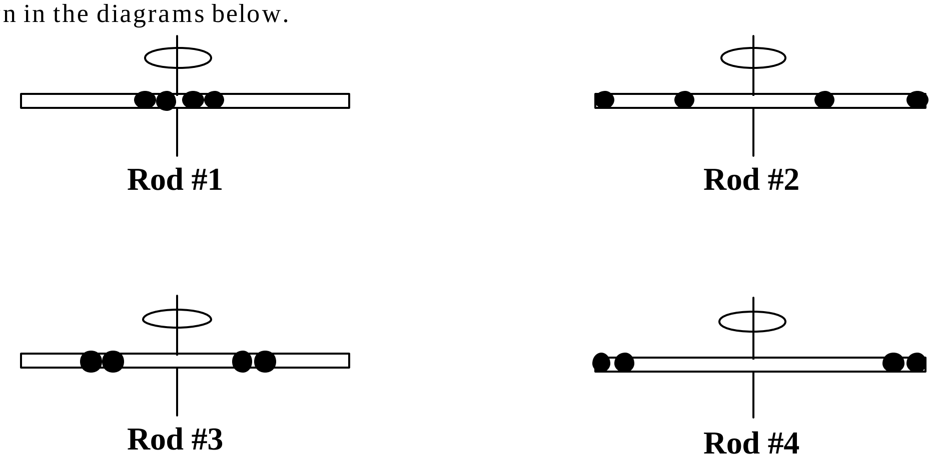
   b. Rank the magnitudes of the torques about the *center* support. Explain your reasoning.

   c. Rank the magnitudes of the torques about an axis perpendicular to the drawing at the *right* end of the stick. Explain your reasoning.

   d. Can the stick be in translational equilibrium? Explain your reasoning.

   e. Can the stick be in rotational equilibrium? Explain your reasoning.

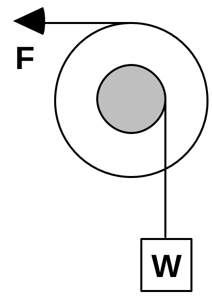
2. Four light beads of mass m are arranged in different ways on four identical light rods, as shown in the diagrams below.



Rank the rotational inertia of the four rods. Explain your reasoning.

☑ CHECK YOUR UNDERSTANDING

3. Two pulleys are firmly attached to each other and rotate on a stationary axle through their centers, as shown at right. A weight **W** is attached to a string wound around the smaller pulley. You pull on the string wound around the larger pulley with just enough force **F** to raise the weight at a constant speed.

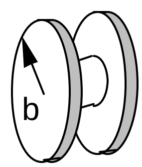


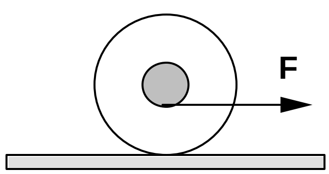
   a. Is the magnitude of **F** greater than, less than, or equal to **W**? Explain.

   b. If you raise the weight a distance h, is the distance that you pulled the string greater than, less than, or equal to h? Explain.

   c. Is the work done by the man greater than, less than or equal to the increase in potential energy of the weight? Explain.

4. A yo-yo is made from two uniform disks of radius b connected by a short cylindrical axle of radius a, as shown at right.

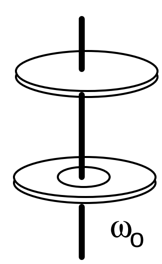




The yo-yo sits on a table. A string is wound around the axle, and one end of the string is pulled by a force **F**. If the force is small enough, the yo-yo rolls without slipping. It rotates *clockwise* as it accelerates to the right.

   a. Write an expression for the total moment of inertia of the yo-yo.
   b. What is the direction of the frictional force exerted on the yo-yo by the table surface? Explain.
   c. Which force, **F** or the frictional force, is greater? Or are the two forces equal? Explain.
   d. Which force exerts the larger torque on the yo-yo, or are the torques equal? Explain.

5. Two identical disks have a common axis. Initially, one of the disks is spinning with an angular frequency w_o. When the two disks are brought into contact, they stick together.



a. Is the final angular frequency greater than, less than, or equal to $w_o/2$? Explain.
b. Is the kinetic energy of the system the same before and after the collision? Explain.

☑ CHECK YOUR UNDERSTANDING

TA Name:____________________________

PHYSICS 1301 LABORATORY REPORT

Laboratory VII

Name and ID#: ____

Date performed: ____________ Day/Time section meets: ________________________

Lab Partners' Names: ____

____

____

Problem # and Title: ____

Lab Instructor's Initials: ________

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

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