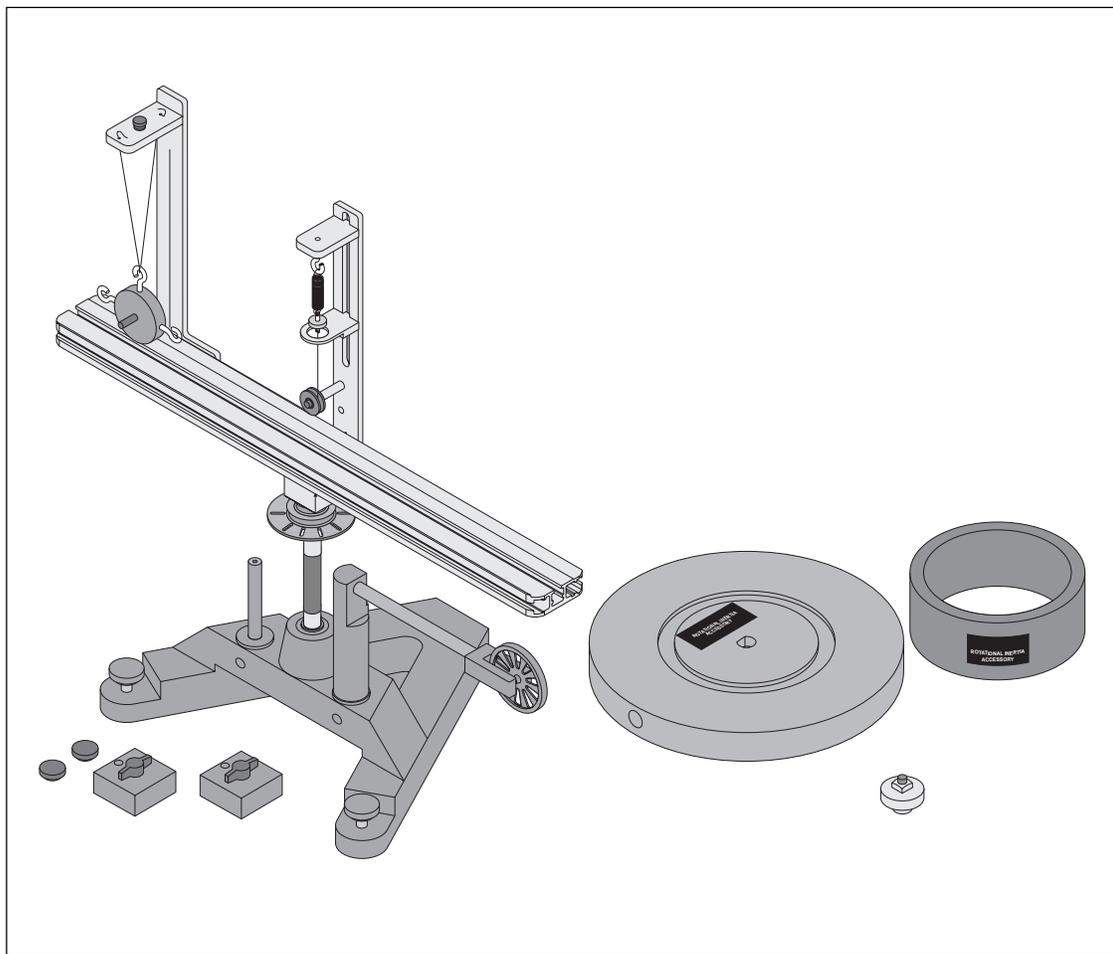


**Instruction Manual and  
Experiment Guide for  
the PASCO scientific  
Model ME-8950**

012-05293E  
8/97

# **COMPLETE ROTATIONAL SYSTEM**



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This manual edited by: Ann and Jon Hanks

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# Introduction

PASCO's Complete Rotational System provides a full range of experiments in centripetal force and rotational dynamics. The system consists of three separate components:

## Description

The ME-8951 Rotating Platform consists of a sturdy 4 kg base with low friction bearings and a rotating arm which serves as a versatile base for rotation experiments. This platform is a general purpose base upon which you may mount anything (having a mass under 3 kg) you wish to rotate. The T-slots in the track supply a convenient way to mount objects to the track using thumbscrews and square nuts. To use the Centripetal Force Accessory (ME-8952) or the Rotational Inertia Accessory (ME-8953), each must be mounted on this base. A photogate/pulley mount and two 300 g masses are also included.

The ME-8952 Centripetal Force Accessory is comprised of two vertical posts which can be mounted to the Rotating Platform with thumbscrews. These posts are adjustable and can be positioned virtually anywhere along the length of the platform. The radius indicator is at the center of the apparatus so it can be clearly seen while the apparatus is rotating. This accessory requires the Rotating Platform (ME-8951) to operate. The PASCO Centripetal Force Accessory can be used to experiment with centripetal force and conservation of angular momentum. For the centripetal force experiments it is possible to vary the mass and radius to see the resulting change in the centripetal force. The force can also be held constant while other quantities are varied. The Centripetal Force Accessory is powered by hand and the rate of rotation can be counted manually or read by a computer. Variable hanging masses are included.

The ME-8953 Rotational Inertia Accessory includes a disk and a metal ring. The disk can be mounted to the rotating base in a variety of positions and at any radius. This accessory requires the Rotating Platform (ME-8951) to operate. The Rotational Inertia Accessory allows you to perform rotational inertia experiments and conservation of angular momentum experiments.

## About This Manual

The following Equipment section describes each component in detail and the subsequent Assembly section provides instructions for component assembly and setup.

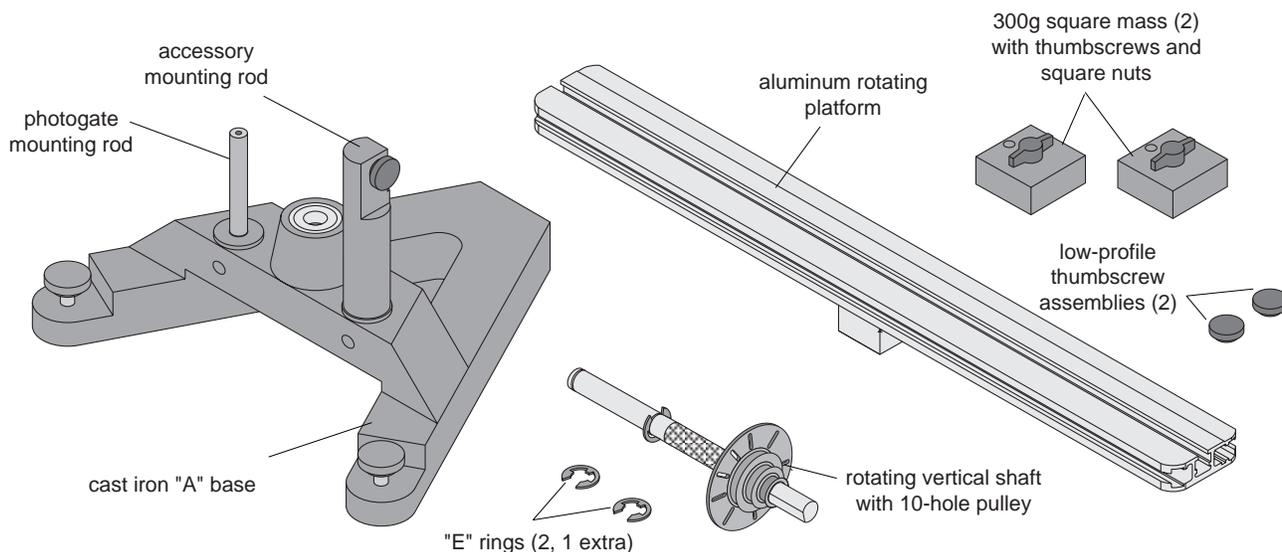
The Experiment section contains several experiments that can illustrate some of the basic theory of centripetal force, rotational inertia, etc.

## Computer Timing

You can use a computer with a PASCO Smart Pulley to measure the motion of the apparatus. Some of the experiments describe how to use the MS-DOS version of Smart Pulley Timer. If you are using the Apple II version of Smart Pulley Timer, the procedure for using the program will be similar.

If you are using a computer interface that comes with its own software (such as the Series 6500 Interface for IBM or Apple II, the CI-6550 Computer Interface for Macintosh, or the CI-6700 MacTimer Timing Interface), refer to the interface manuals for instructions on how to use the software with the Smart Pulley.

# Equipment

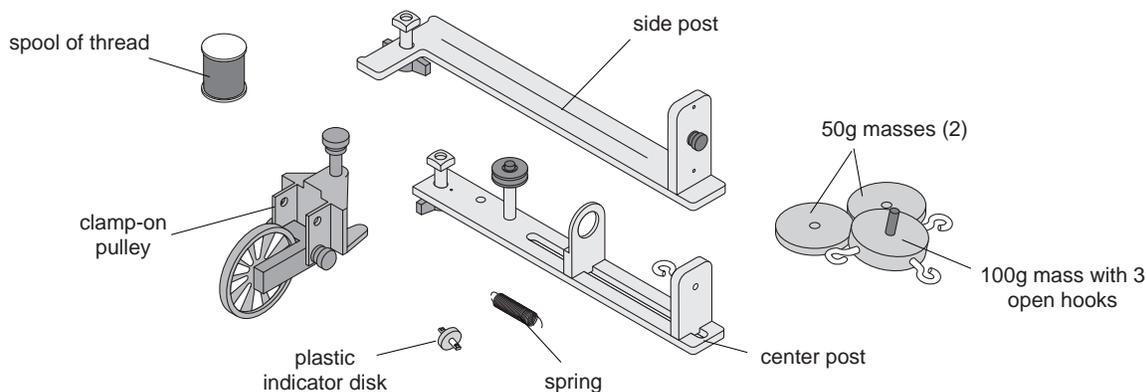


### ME-8951 Rotating Platform Equipment

**The ME-8951 Rotating Platform Includes the following:**

- PASCO cast iron “A” base with rotating shaft and pulley with 10 holes
- aluminum track
- two square masses (about 300 g) with thumb screw and square nut

- two additional low-profile screws and square nuts to act as stops for the square mass in the Conservation of Angular Momentum experiment
- accessory mounting rod for mounting the 10-spoke pulley or the optional Smart Pulley photogate head
- accessory mounting rod for mounting PASCO Photogate (ME-9498A, ME-9402B or later)

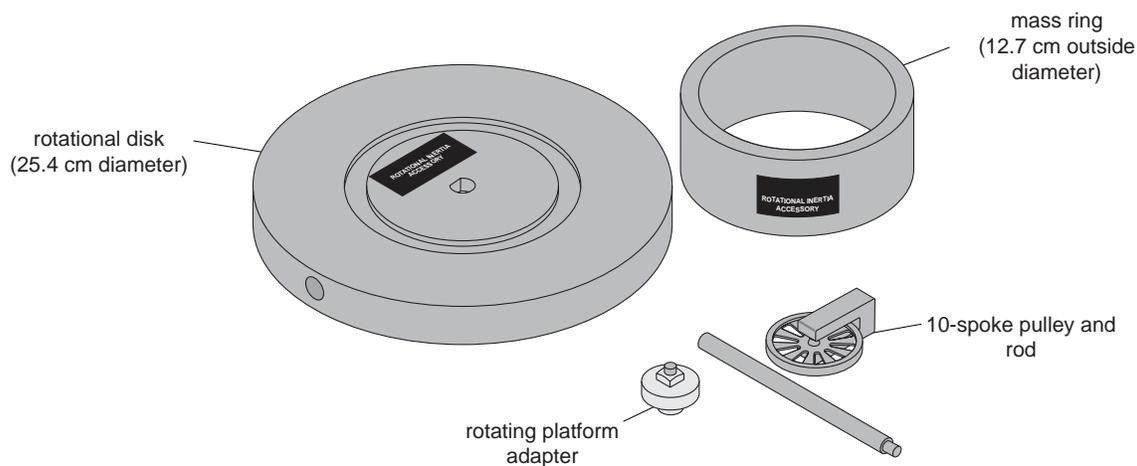


### ME-8952 Centripetal Force Accessory Equipment

**The ME-8952 Centripetal Force Accessory includes:**

- center post that supports an indicator mechanism which consists of a small pulley, a movable spring holder, a movable indicator, a spring, and a plastic indicator disk
- side post for hanging hooked mass

- mass (100 g) with 3 open hooks
- 2 additional 50 gram masses
- clamp-on pulley
- 1 spool of thread



### ME-8953 Rotational Inertia Accessory Equipment

#### The ME-8953 Rotation Inertia Accessory includes:

- disk with bearings in the center
- ring (12.7 cm diameter)
- adapter to connect disk to platform
- 10-spoke pulley and rod

#### Other Equipment Needed:

The following is a list of equipment recommended for the experiments described in this manual. See the PASCO catalog for more information.

- Projectile Launcher
- Projectile Collision Accessory
- Smart Pulley (with Smart Pulley Timer software, or a compatible computer interface)
- string
- mass and hanger set
- balance (for measuring mass)
- calipers
- stopwatch

#### Miscellaneous Supplies:

- meter stick
- graph paper
- carbon paper
- white paper
- rubber bands
- paper clips

# Assembly

## ME-8951 Rotating Platform

### Assembling the Rotating Platform

- ① Insert the cylindrical end of the shaft into the bearings on the top-side of the A-shaped iron base. Secure the shaft in place by inserting the "E" ring in the slot at the bottom of the shaft. See Figure 1.
- ② Mount the track to the shaft and tighten the thumb screw against the flat side of the "D" on the shaft. See Figure 1.

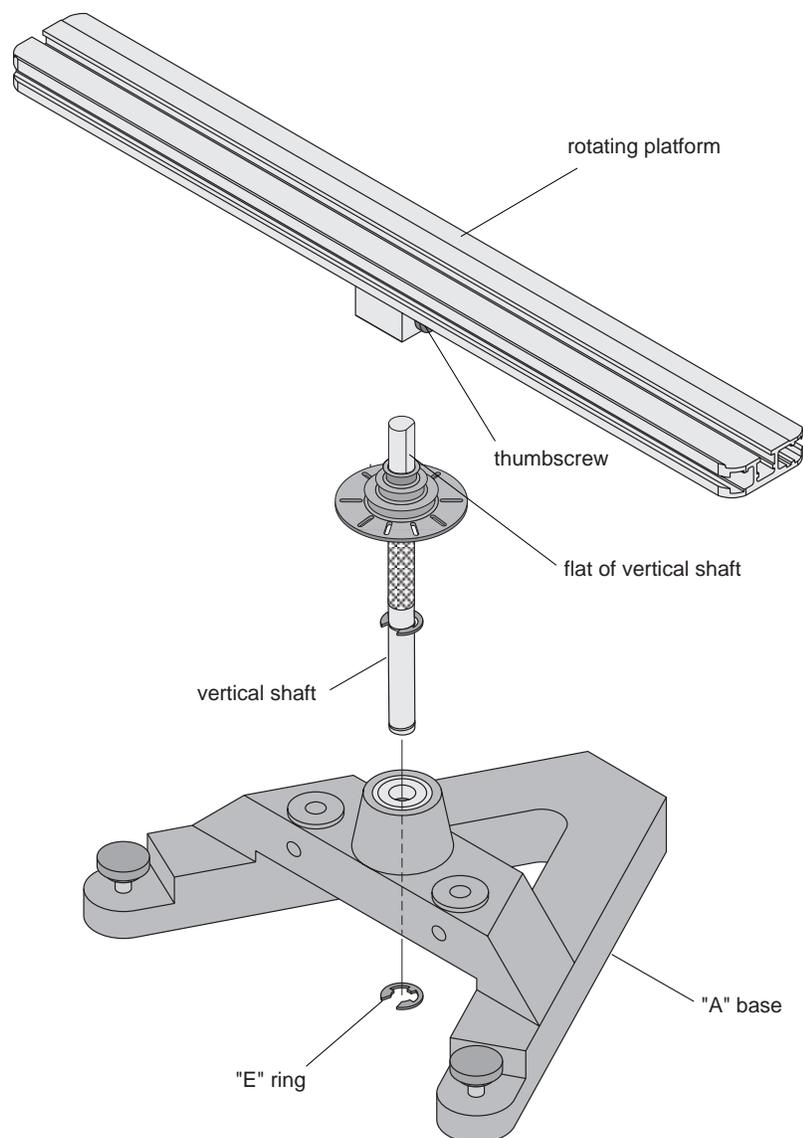
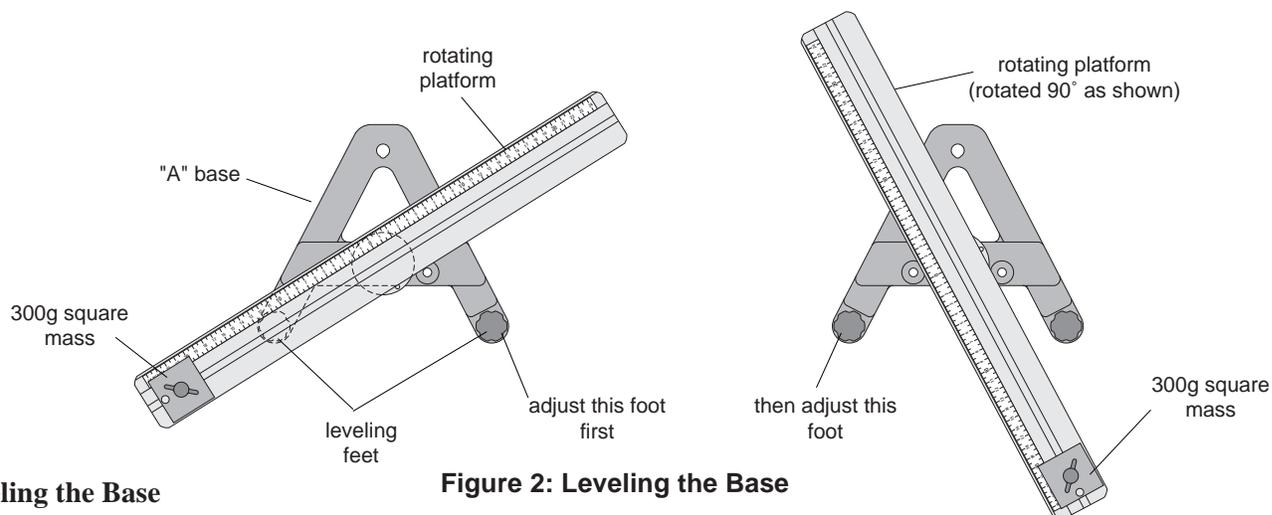


Figure 1: Attaching the Vertical Shaft to the Base and Rotating Platform Assembly



**Figure 2: Leveling the Base**

### Leveling the Base

Some experiments (such as the Centripetal Force experiments) require the apparatus to be extremely level. If the track is not level, the uneven performance will affect the results. To level the base, perform the following steps:

- ① Purposely make the apparatus unbalanced by attaching the 300 g square mass onto either end of the aluminum track. Tighten the screw so the mass will not slide. If the hooked mass is hanging from the side post in the centripetal force accessory, place the square mass on the same side.
- ② Adjust the leveling screw on one of the legs of the base until the end of the track with the square mass is aligned over the leveling screw on the other leg of the base. See Figure 2.
- ③ Rotate the track 90 degrees so it is parallel to one side of the “A” and adjust the other leveling screw until the track will stay in this position.
- ④ The track is now level and it should remain at rest regardless of its orientation.

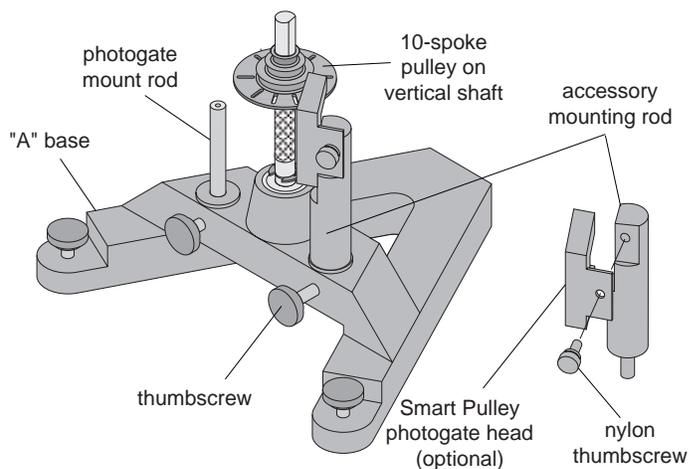
### Installing the Optional Smart Pulley Photogate Head

The black plastic rod stand is designed to be used in two ways:

- It can be used to mount a Smart Pulley photogate head to the base in the correct position to use the 10 holes in the pulley on the rotating shaft to measure angular speed.
- It can be used to mount a Smart Pulley (with the pulley and rod) to the base to run a string over the pulley.

#### To Use the Photogate Head Only:

- ① To install, first mount the black rod to the base by inserting the rod into either hole adjacent to the center shaft on the base.
- ② Mount the Smart Pulley photogate head horizontally with the cord side down. Align the screw hole in the photogate head with the screw hole in the flat side of the black rod. Secure the photogate head with the thumb screw. See Figure 3.
- ③ Loosen the thumb screw on the base to allow the black rod to rotate. Orient the rod and photogate head so the infrared beam passes through the holes



**Figure 3: Using the Accessory Mounting Rod With the Smart Pulley**

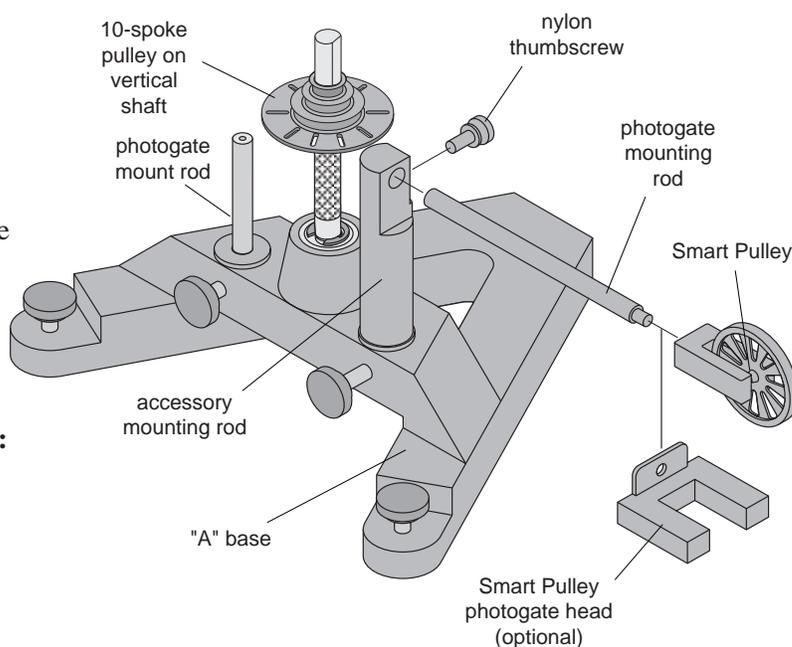
in the pulley. If the photogate head is powered by a computer, you can tell when the photogate is blocked by watching the LED indicator on the end of the photogate. The photogate head should not be rubbing against the pulley. When the head is in the correct position, tighten the bottom screw to fix the rod in place.

**To use the entire Smart Pulley with rod or the Super Pulley with rod:**

- ① Insert the Smart Pulley rod into the hole in the black rod and tighten the set screw against the Smart Pulley rod. See Figure 4.
- ② Rotate the black rod so the string from the pulley on the center shaft is aligned with the slot on the Smart Pulley.
- ③ Adjust the position of the base so the string passing over the Smart Pulley will clear the edge of the table.

**To mount a PASCO Photogate on "A" base:**

- ① Mount PASCO Photogate on threaded end of rod (rod height may be adjusted with thumbscrew).
- ② Slide non-threaded end of photogate mount into hole in base, clamp in place with thumbscrew.



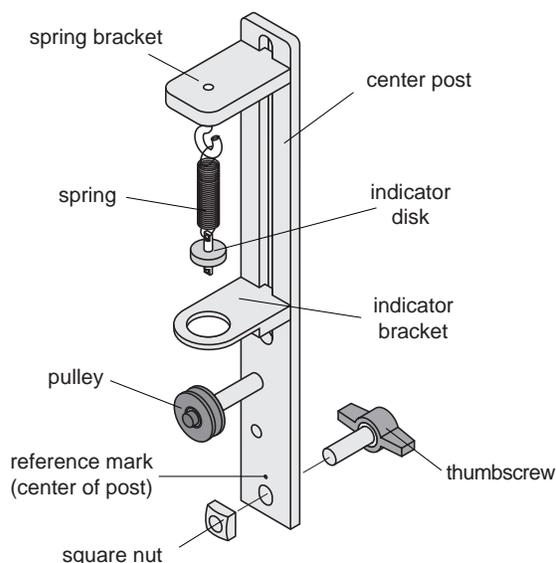
**Figure 4: Using the Accessory Mounting Rod With the Photogate Mounting Rod and/or Smart Pulley**

**ME-8952 Centripetal Force Accessory**

**Center Post Assembly**

Assemble the center post as shown in Figure 5:

- ① Attach one end of the spring to the spring bracket and connect the indicator disk to the other end of the spring. Insert the spring bracket into the slot on the center post and tighten the thumb screw.
- ② Tie one end of a string (about 30 cm long) to the bottom of the indicator disk and tie a loop in the other end of the string.
- ③ Insert the indicator bracket into the slot on the center post, placing it below the spring bracket. Tighten the thumb screw.
- ④ Attach the pulley in the higher of the two holes on the center bracket.
- ⑤ Insert the thumb screw at the bottom of the center post and attach the square nut.

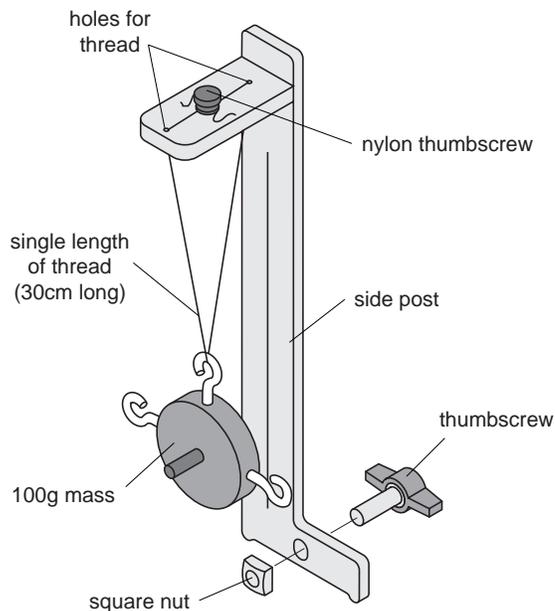


**Figure 5: Center Post Assembly**

### Side Post Assembly

Assemble the side post as shown in Figure 6:

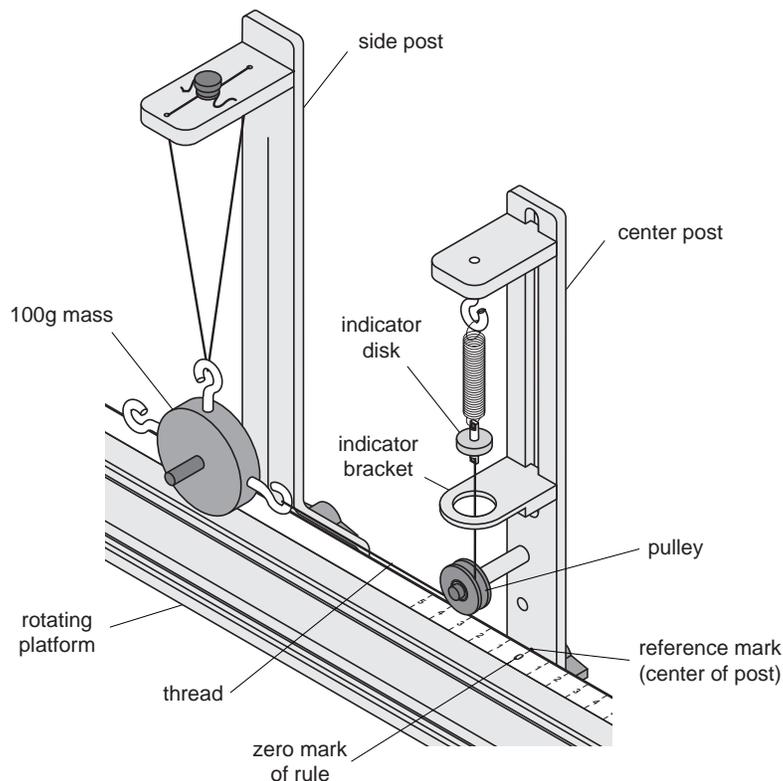
- ① Insert the thumb screw at the bottom of the side post and attach the square nut.
- ② Using a string about 30 cm long, tie the string around the screw head on the top of the side post. Then thread the other end of the string down through one of the holes in the top of the side post and then back up through the other hole. Do not pull the string taut.
- ③ Loosen the screw on the top of the side post and wrap the loose end of the string around the threads of the screw and tighten the screw.



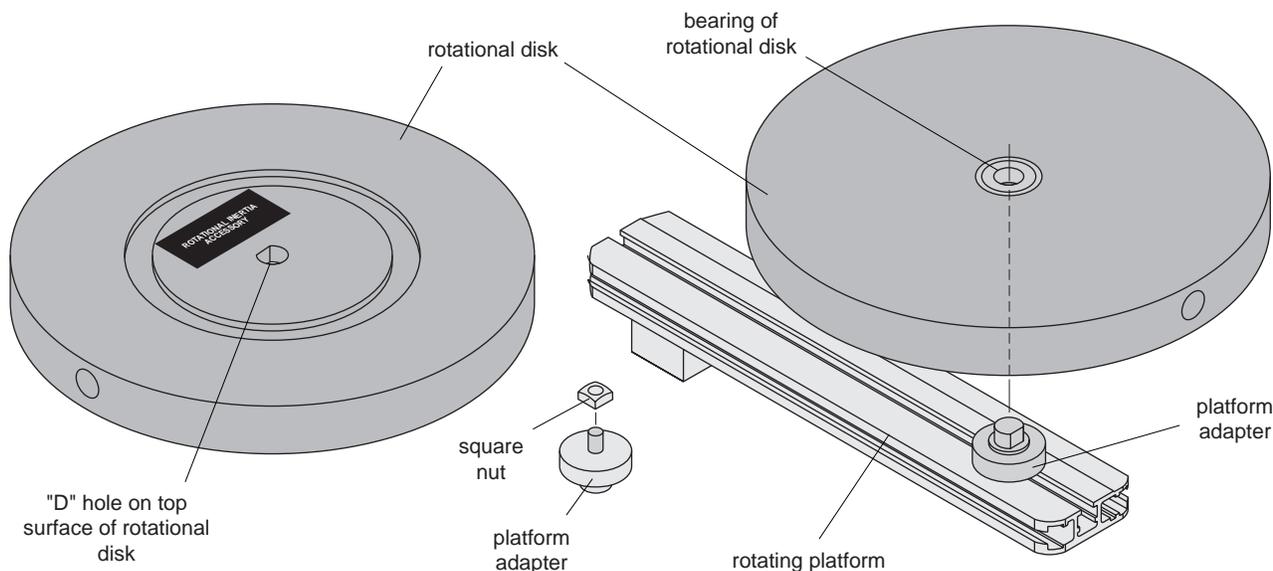
**Figure 6: Side Post Assembly**

### Threading the Centripetal Force Accessory

- ① Mount the center post in the T-slot on the side of the track that has the rule. Align the line on the center post with the zero mark on the rule and tighten the thumb screw to secure it in place. Then mount the side post on the same side of the track. See Figure 7.
- ② Hang the object from the string on the side post and adjust the height of the object so the string coming from the center post will be level.



**Figure 7: Threading the Centripetal Force Accessory**



**Figure 8: Rotational Inertia Accessory Including Platform Adapter Assembly**

## ME-8953 Rotational Inertia Accessory

### Rotational Inertia Accessory Assembly

Little assembly is required to use the Rotational Inertia Accessory. The rotational disk can be placed directly onto the axle of the rotating base or can be used with the rotating platform via the included platform adapter.

### Platform Adapter Assembly

- ① Attach the square nut (supplied with the Rotational Inertia Accessory) to the platform adapter.
- ② Position the platform adapter at the desired radius as shown in Figure 8.
- ③ Grip the knurled edge of the platform adapter and tighten.

The rotating disk can be mounted in a variety of positions using any of the four holes on the rotation disk.

- Two “D” holes exist on the edge of the disk, located at 180° from one another.
- One “D” hole is located at the center on the top surface (the surface with the metal ring channel and the PASCO label) of the disk.
- One hole is located at the center on the bottom surface of the disk and is actually the inner race of a bearing. This enables the rotational disk to rotate (in either direction) in addition to other rotating motions applied to your experiment setup.

# Experiment 1: Conservation of Angular Momentum: Ball Shot Into Catcher on Rotating Track

## EQUIPMENT NEEDED

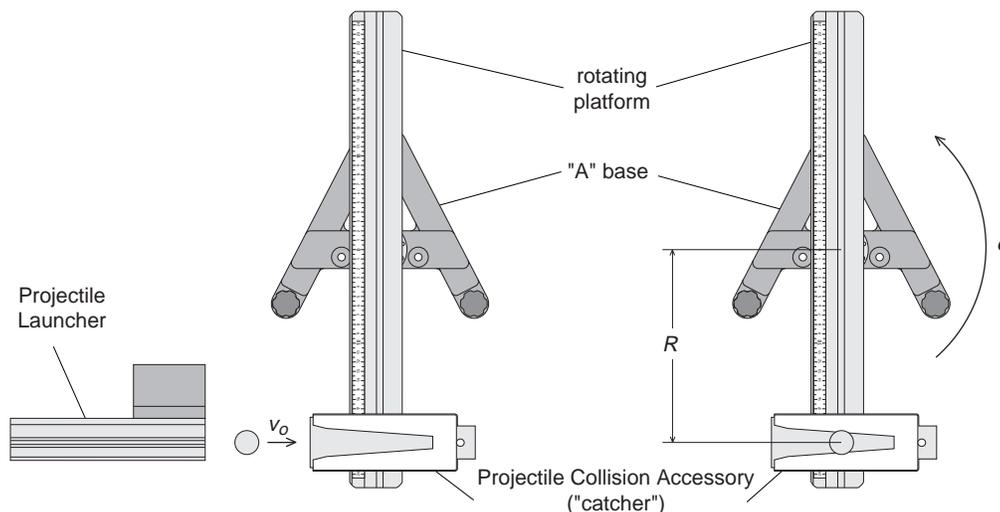
- |  |                                |
|--|--------------------------------|
| - Rotating Platform (ME-8951)              | - Rubber band                  |
| - Projectile Launcher (ME-6800)            | - white paper and carbon paper |
| - Projectile Collision Accessory (ME-6815) | - thread                       |
| - Smart Pulley Photogate                   | - meter stick                  |
| - Smart Pulley Timer software              | - mass and hanger set          |

## Purpose

The muzzle velocity of the Projectile Launcher can be determined by shooting the ball into the catcher mounted on the track and conserving angular momentum during the collision. This result can be checked by finding the muzzle velocity of the Launcher by shooting the ball horizontally off the table.

## Theory

A ball is launched horizontally and embeds in the catcher mounted on the platform. The platform then rotates. See Figure 1.1.



**Figure 1.1 Conservation of Angular Momentum**

Angular momentum is conserved during the collision but energy is not conserved. The angular momentum before the collision is equal to the angular momentum after the collision:

$$L = m_b v_0 R = I \omega$$

where  $m_b$  is the mass of the ball,  $v_0$  is the muzzle velocity of the ball,  $R$  is the distance between the ball and the axis of rotation,  $I$  is the rotational inertia of the catcher, ball, and track after the collision, and  $\omega$  is the angular velocity of the system immediately after the collision. Solving for the muzzle velocity of the ball gives:

$$v_0 = \frac{I \omega}{m_b R}$$

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since  $\tau = I\alpha$ ,

$$I = \frac{\tau}{\alpha}$$

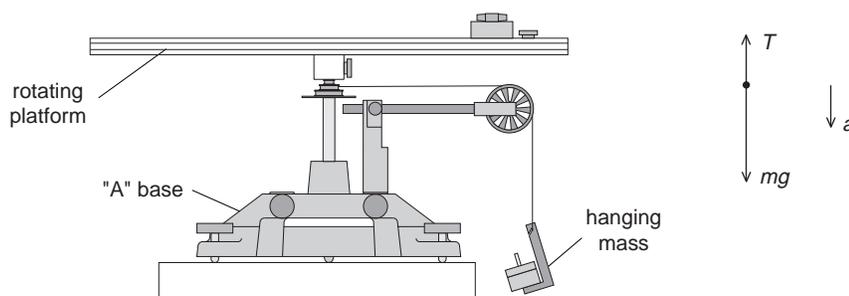
where  $\alpha$  is the angular acceleration which is equal to  $a/r$  and  $\tau$  is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where  $r$  is the radius of the cylinder about which the thread is wound and  $T$  is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass,  $m$ , gives (See Figure 1.2).

$$\Sigma F = mg - T = ma$$



**Figure 1.2: Rotational Apparatus and Free-Body Diagram**

So, solving for the tension in the thread gives:

$$T = m(g - a)$$

So, once the linear acceleration of the mass ( $m$ ) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

For comparison, the initial speed (muzzle velocity) of the ball is determined by shooting the ball horizontally off the table onto the floor and measuring the vertical and horizontal distances through which the ball travels.

For a ball shot horizontally off a table with an initial speed,  $v_o$ , the horizontal distance traveled by the ball is given by  $x = v_o t$ , where  $t$  is the time the ball is in the air. No air friction is assumed.

The vertical distance the ball drops in time  $t$  is given by  $y = \frac{1}{2}gt^2$ .

The initial velocity of the ball can be determined by measuring  $x$  and  $y$ . The time of flight of the ball can be found using:

$$t = \sqrt{\frac{2y}{g}}$$

and then the muzzle velocity can be found using  $v_o = x/t$ .

## Part I: Determining the initial velocity of the ball

### Setup

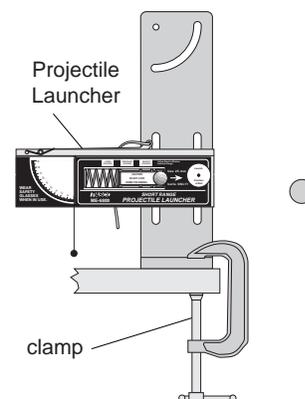
- ① Clamp the Projectile Launcher to a sturdy table near one end of the table.
- ② Adjust the angle of the Projectile Launcher to zero degrees so the ball will be shot off horizontally. See Figure 1.3.

### Procedure

- ① Put the ball into the Projectile Launcher and cock it to the long range position. Fire one shot to locate where the ball hits the floor. At this position, tape a piece of white paper to the floor. Place a piece of carbon paper (carbon-side down) on top of this paper and tape it down. When the ball hits the floor, it will leave a mark on the white paper.
- ② Fire about ten shots.
- ③ Measure the vertical distance from the bottom of the ball as it leaves the barrel (this position is marked on the side of the barrel) to the floor. Record this distance in Table 1.1.
- ④ Use a plumb bob to find the point on the floor that is directly beneath the release point on the barrel. Measure the horizontal distance along the floor from the release point to the leading edge of the paper. Record in Table 1.1.
- ⑤ Measure from the leading edge of the paper to each of the ten dots and record these distances in Table 1.1.
- ⑥ Find the average of the ten distances and record in Table 1.1.
- ⑦ Using the vertical distance and the average horizontal distance, calculate the time of flight and the initial velocity of the ball. Record in Table 1.1 and Table 1.4.

### Alternate Method: Determining the Muzzle Velocity with Photogates

- ① Attach the photogate bracket to the Launcher and attach two photogates to the bracket. Plug the photogates into a computer or other timer.
- ② Put the ball into the Projectile Launcher and cock it to the long range position.
- ③ Run the timing program and set it to measure the time between the ball blocking the two photogates.



**Figure 1.3 Projectile Launcher Setup**

**Table 1.1 Determining the Initial Velocity**

Vertical distance = \_\_\_\_\_

Horizontal distance to edge of paper = \_\_\_\_\_

Initial velocity = \_\_\_\_\_

Trial Number	Distance
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average	
Total Distance	

- ④ Shoot the ball three times and take the average of these times. Record in Table 1.2.
- ⑤ Using that the distance between the photogates is 10 cm, calculate the initial speed and record it in Table 1.2 and Table 1.4.

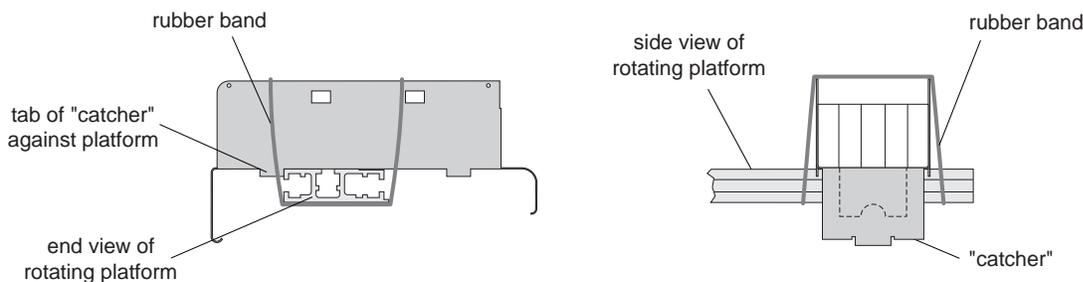
**Table 1.2 Initial Speed Using Photogates**

Trial Number	Time
1	
2	
3	
Average Time	
Initial Speed	

## Part II: Conservation of Angular Momentum

### Setup

- ① Find the mass of the ball and record it in Table 1.3.
- ② Attach the ball catcher to the track using a rubber band as shown in Figure 1.4.



**Figure 1.4: Attaching the Catcher to the Track**

- ③ With the Projectile Launcher mounted as it was in Part I, aim the launcher directly down the middle of the ball catcher using the sights inside the projectile launcher. Clamp the launcher to the table.
- ④ Attach the Smart Pulley photogate to the base, using the black rod. Connect the photogate to a computer and run Smart Pulley Timer.

### Procedure

- ① Load the Launcher with the steel ball on the long range setting.
- ② Make sure the rotating platform is at rest and fire the ball into the catcher. Record the angular speed of the platform in Table 1.3. Repeat for a total of five shots.
- ③ Measure the distance from the axis of rotation to the ball in the catcher and record in Table 1.3.

**Table 1.3 Data Mass of Ball**

Angular Speed

## Part III: Determining the Rotational Inertia

### Setup

- ① Attach a Smart Pulley with rod to the base using the black rod.
- ② Wind a thread around the pulley on the center shaft and pass the thread over the Smart Pulley.

### Procedure

#### Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this “friction mass” will be subtracted from the mass used to accelerate the apparatus.

From the Main Menu select <V>, display velocity

To find the mass required to overcome kinetic friction run “Display Velocity”:

- ① Select <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.
- ② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures.
- ③ Press <RETURN> to stop displaying the velocity. Record this friction mass in Table 1.4.

#### Finding the Acceleration of the Apparatus

To find the acceleration, put about 30 g (Record the exact hanging mass in Table 1.4) over the pulley and run “Motion Timer”:

- ① Select <M>-Motion Timer <RETURN>. Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.
- ② Wait for the computer to calculate the times and then press <RETURN>.

To find the acceleration, graph velocity versus time:

- ③ Choose <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.
- ④ The graph will now be plotted and the slope =  $m$  will be displayed at the top of the graph. This slope is the acceleration. Push <RETURN> and <X> twice to return to the Main Menu.

#### Measure the Radius

- ① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius.
- ② Record the radius in Table 1.4.

**Table 1.4 Rotational Inertia Data**

Friction Mass	
Hanging Mass	
Slope	
Radius	

## Analysis

- ① Calculate the average of the angular speeds in Table 1.3 and record the result in Table 1.5.
- ② Calculate the rotational inertia:
  - Subtract the “friction mass” from the hanging mass used to accelerate the apparatus to determine the mass,  $m$ , to be used in the equations.
  - Calculate the experimental value of the rotational inertia and record it in Table 1.5.
- ③ Using the average angular speed, the rotational inertia, and the distance,  $r$ , calculate the muzzle velocity of the ball and record it in Table 1.5.
- ④ Calculate the percent difference between the muzzle velocities found in Parts I and II. Record in Table 1.5.

**Table 1.5 Results**

Average Angular Speed	
Rotational Inertia	
Calculated Muzzle Velocity, $v_0$	
Muzzle Velocity	
% Difference	

## Questions

- ① What percentage of the kinetic energy is lost in the collision? Use the masses and velocities to calculate this percentage.

$$\% \text{ Lost} = \frac{KE_{\text{before}} - KE_{\text{after}}}{KE_{\text{before}}} \times 100\%$$

## Experiment 2: Rotational Inertia of a Point Mass

### EQUIPMENT REQUIRED

- |   |  |
|---|--|
| <ul style="list-style-type: none"> <li>- Precision Timer Program</li> <li>- paper clips (for masses &lt; 1 g)</li> <li>- triple beam balance</li> </ul> | <ul style="list-style-type: none"> <li>- mass and hanger set</li> <li>- 10-spoke pulley with photogate head</li> <li>- calipers</li> </ul> |
|---|--|

### Purpose

The purpose of this experiment is to find the rotational inertia of a point mass experimentally and to verify that this value corresponds to the calculated theoretical value.

### Theory

Theoretically, the rotational inertia,  $I$ , of a point mass is given by  $I = MR^2$ , where  $M$  is the mass,  $R$  is the distance the mass is from the axis of rotation.

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since  $\tau = I\alpha$ ,

$$I = \frac{\tau}{\alpha}$$

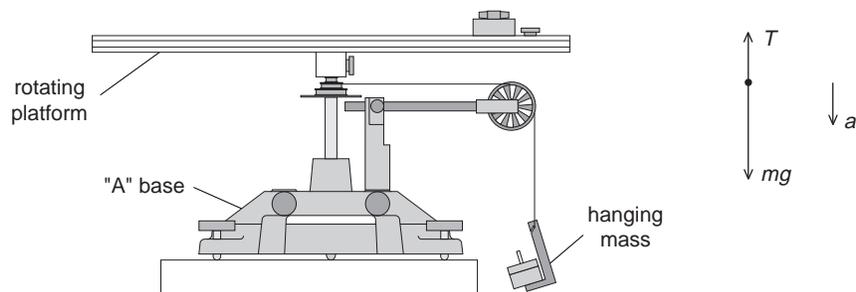
where  $\alpha$  is the angular acceleration which is equal to  $a/r$  and  $\tau$  is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where  $r$  is the radius of the cylinder about which the thread is wound and  $T$  is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass,  $m$ , gives (see Figure 2.1).

$$\Sigma F = mg - T = ma$$



**Figure 2.1: Rotational Apparatus and Free-Body Diagram**

Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the linear acceleration of the mass ( $m$ ) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

### Setup

- ① Attach the square mass (point mass) to the track on the rotating platform at any radius you wish.
- ② Mount the Smart Pulley to the base and connect it to a computer. See Figure 2.2.
- ③ Run the Smart Pulley Timer program.

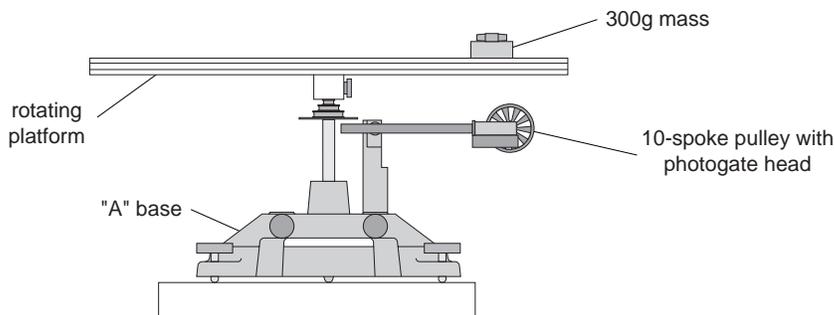


Figure 2.2: Rotational inertia of a point mass

### Procedure

#### ***Part I: Measurements For the Theoretical Rotational Inertia***

- ① Weigh the square mass to find the mass  $M$  and record in Table 2.1.
- ② Measure the distance from the axis of rotation to the center of the square mass and record this radius in Table 2.1.

Table 2.1: Theoretical Rotational Inertia

Mass	
Radius	

#### ***Part II: Measurement For the Experimental Method***

### Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this “friction mass” will be subtracted from the mass used to accelerate the ring.

- ① To find the mass required to overcome kinetic friction run “Display Velocity”: <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.
- ② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity.

### Finding the Acceleration of the Point Mass and Apparatus

- ① To find the acceleration, put about 50 g over the pulley and run “Motion Timer”: <M>-Motion Timer <RETURN> Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.
- ② Wait for the computer to calculate the times and then press <RETURN>. To find the acceleration, graph velocity versus time: <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.
- ③ The graph will now be plotted and the slope =  $m$  will be displayed at the top of the graph. This slope is the acceleration. Record it in Table 2.2. Push <RETURN> and <X> twice to return to the Main Menu.

Table 2.2: Rotational Inertia Data

	Point Mass and Apparatus	Apparatus Alone
Friction Mass		
Hanging Mass		
Slope		
Radius		

### Measure the Radius

- ① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record in Table 2.2.

### Finding the Acceleration of the Apparatus Alone

Since in **Finding the Acceleration of the Point Mass and Apparatus** the apparatus is rotating as well as the point mass, it is necessary to determine the acceleration, and the rotational inertia, of the apparatus by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the point mass.

- ① Take the point mass off the rotational apparatus and repeat **Finding the Acceleration of the Point Mass and Apparatus** for the apparatus alone.

► NOTE: that it will take less “friction mass” to overcome the new kinetic friction and it is only necessary to put about 20 g over the pulley in **Finding the Acceleration of the Point Mass and Apparatus**.

- ② Record the data in Table 2.2.

### Calculations

- ① Subtract the “friction mass” from the hanging mass used to accelerate the apparatus to determine the mass,  $m$ , to be used in the equations.
- ② Calculate the experimental value of the rotational inertia of the point mass and apparatus together and record in Table 2.3.
- ③ Calculate the experimental value of the rotational inertia of the apparatus alone. Record in Table 2.3.

- ④ Subtract the rotational inertia of the apparatus from the combined rotational inertia of the point mass and apparatus. This will be the rotational inertia of the point mass alone. Record in Table 2.3.
- ⑤ Calculate the theoretical value of the rotational inertia of the point mass. Record in Table 2.3.
- ⑥ Use a percent difference to compare the experimental value to the theoretical value. Record in Table 2.3.

**Table 2.3: Results**

Rotational Inertia for Point Mass and Apparatus Combined	
Rotational Inertia for Apparatus Alone	
Rotational Inertia for Point Mass (experimental value)	
Rotational Inertia for Point Mass (theoretical value)	
% Difference	

## **Experiment 3: Centripetal Force**

### **EQUIPMENT NEEDED**

- |  |   |
|--|---|
| <ul style="list-style-type: none"> <li>- Centripetal Force Accessory (ME-8952)</li> <li>- stopwatch</li> <li>- graph paper (2 sheets)</li> <li>- string</li> </ul> | <ul style="list-style-type: none"> <li>- Rotating Platform (ME-8951)</li> <li>- balance</li> <li>- mass and hanger set</li> </ul> |
|--|---|

### **Purpose**

The purpose of this experiment is to study the effects of varying the mass of the object, the radius of the circle, and the centripetal force on an object rotating in a circular path.

### **Theory**

When an object of mass  $m$ , attached to a string of length  $r$ , is rotated in a horizontal circle, the centripetal force on the mass is given by:

$$F = \frac{mv^2}{r} = mr\omega^2$$

where  $v$  is the tangential velocity and  $\omega$  is the angular speed ( $v = r\omega$ ). To measure the velocity, the time for one rotation (the period,  $T$ ) is measured. Then:

$$v = \frac{2\pi r}{T}$$

and the centripetal force is given by:

$$F = \frac{4\pi^2 mr}{T^2}$$

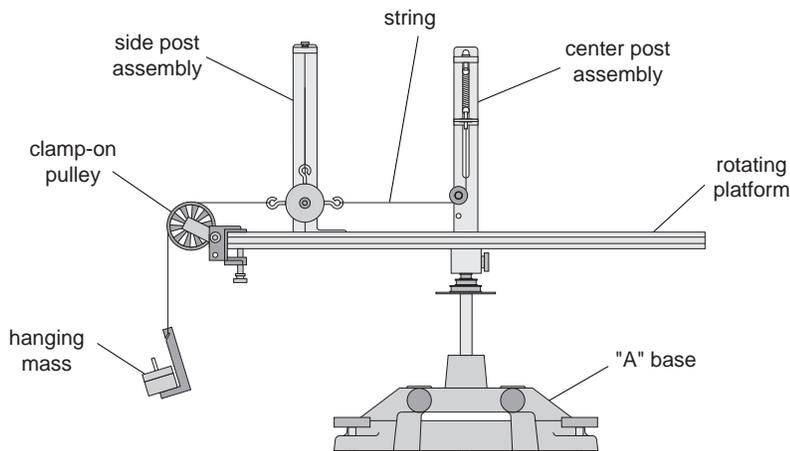
### **Setup**

Level the "A" base and rotating platform as described in the ME-8951 assembly section on page 5.

### **Procedure**

#### **Part I: Vary Radius (constant force and mass)**

- ① The centripetal force and the mass of the hanging object will be held constant for this part of the experiment. Weigh the object and record its mass in Table 3.1. Hang the object from the side post and connect the string from the spring to the object. The string must pass under the pulley on the center post. See Figure 3.1.



**Figure 3.1: Centripetal Force Apparatus**

- ② Attach the clamp-on pulley to the end of the track nearer to the hanging object. Attach a string to the hanging object and hang a known mass over the clamp-on pulley. Record this mass in Table 3.1. This establishes the constant centripetal force.
- ③ Select a radius by aligning the line on the side post with any desired position on the measuring tape. While pressing down on the side post to assure that it is vertical, tighten the thumb screw on the side post to secure its position. Record this radius in Table 3.1.
- ④ The object on the side bracket must hang vertically: On the center post, adjust the spring bracket vertically until the string from which the object hangs on the side post is aligned with the vertical line on the side post.
- ⑤ Align the indicator bracket on the center post with the orange indicator.
- ⑥ Remove the mass that is hanging over the pulley and remove the pulley.
- ⑦ Rotate the apparatus, increasing the speed until the orange indicator is centered in the indicator bracket on the center post. This indicates that the string supporting the hanging object is once again vertical and thus the hanging object is at the desired radius.
- ⑧ Maintaining this speed, use a stopwatch to time ten revolutions. Divide the time by ten and record the period in Table 3.1.
- ⑨ Move the side post to a new radius and repeat the procedure. Do this for a total of five radii.

**Table 3.1: Varying the Radius**

Mass of the object = \_\_\_\_\_  
 Mass hanging over the pulley = \_\_\_\_\_  
 Slope from graph = \_\_\_\_\_

Radius	Period (T)	T <sup>2</sup>

**Analysis**

- ① The weight of the mass hanging over the pulley is equal to the centripetal force applied by the spring. Calculate this force by multiplying the mass hung over the pulley by “g” and record this force at the top of Table 3.2.

- ② Calculate the square of the period for each trial and record this in Table 3.1.
- ③ Plot the radius versus the square of the period. This will give a straight line since:

$$r = \left( \frac{F}{4\pi^2 m} \right) T^2$$

- ④ Draw the best-fit line through the data points and measure the slope of the line. Record the slope in Table 3.1.

**Table 3.2: Results (varying radius)**

- ⑤ Calculate the centripetal force from the slope and record in Table 3.2.
- ⑥ Calculate the percent difference between the two values found for the centripetal force and record in Table 3.2.

Centripetal Force = $mg$	
Centripetal Force From Slope	
Percent Difference	

## **Part II: Vary Force (constant radius and mass)**

The radius of rotation and the mass of the hanging object will be held constant for this part of the experiment.

- ① Weigh the object and record its mass in Table 3.3. Hang the object from the side post and connect the string from the spring to the object. The string must pass under the pulley on the center post.
- ② Attach the clamp-on pulley to the end of the track nearer to the hanging object. Attach a string to the hanging object and hang a known mass over the clamp-on pulley. Record this mass in Table 3.3. This determines the centripetal force.
- ③ Select a radius by aligning the line on the side post with any desired position on the measuring tape. While pressing down on the side post to assure that it is vertical, tighten the thumb screw on the side post to secure its position. Record this radius in Table 3.3.
- ④ The object on the side bracket must hang vertically: On the center post, adjust the spring bracket vertically until the string from which the object hangs on the side post is aligned with the vertical line on the side post.
- ⑤ Align the indicator bracket on the center post with the orange indicator.
- ⑥ Remove the mass that is hanging over the pulley and remove the pulley.
- ⑦ Rotate the apparatus, increasing the speed until the orange indicator is centered in the indicator bracket on the center post. This indicates that the string supporting the hanging object is once again vertical and thus the hanging object is at the desired radius.
- ⑧ Maintaining this speed, use a stopwatch to time ten revolutions. Divide the time by ten and record the period in Table 3.3.
- ⑨ To vary the centripetal force, clamp the pulley to the track again and hang a different mass over the pulley. Keep the radius constant and repeat the procedure from Step #4. Do this for a total of five different forces.

**Table 3.3: Varying the Centripetal Force**

Mass of the object = \_\_\_\_\_

Radius = \_\_\_\_\_

Slope from graph = \_\_\_\_\_

Mass Over Pulley	Centripetal Force = mg	Period (T)	$\frac{1}{T^2}$

**Analysis**

- ① The weight of the mass hanging over the pulley is equal to the centripetal force applied by the spring. Calculate this force for each trial by multiplying the mass hung over the pulley by “g” and record the results in Table 3.3.
- ② Calculate the inverse of the square of the period for each trial and record this in Table 3.3.
- ③ Plot the centripetal force versus the inverse square of the period. This will give a straight line since:

$$F = \frac{4\pi^2 mr}{T^2}$$

- ④ Draw the best-fit line through the data points and measure the slope of the line. Record the slope in Table 3.3.

**Table 3.4: Results (varying the centripetal force)**

- ⑤ Calculate the mass of the object from the slope and record in Table 3.4.

Mass of Object (from scale)	
Mass of Object (from slope)	
Percent Difference	

- ⑥ Calculate the percent difference between the two values found for the mass of the object and record in Table 3.4.

**Part III: Vary Mass (constant radius and force)**

The centripetal force and the radius of rotation will be held constant for this part of the experiment.

- ① Weigh the object with the additional side masses in place. Record its mass in Table 3.5. Hang the object from the side post and connect the string from the spring to the object. The string must pass under the pulley on the center post.
- ② Attach the clamp-on pulley to the end of the track nearer to the hanging object. Attach a string to the hanging object and hang a known mass over the clamp-on pulley. Record this mass in Table 3.5. This establishes the constant centripetal force.
- ③ Select a radius by aligning the line on the side post with any desired position on the measuring tape. While pressing down on the side post to assure that it is vertical, tighten the thumb screw on the side post to secure its position. Record this radius in Table 3.5.

- ④ The object on the side bracket must hang vertically: On the center post, adjust the spring bracket vertically until the string from which the object hangs on the side post is aligned with the vertical line on the side post.
- ⑤ Align the indicator bracket on the center post with the orange indicator.
- ⑥ Remove the mass that is hanging over the pulley and remove the pulley.
- ⑦ Rotate the apparatus, increasing the speed until the orange indicator is centered in the indicator bracket on the center post. This indicates that the string supporting the hanging object is once again vertical and thus the hanging object is at the desired radius.
- ⑧ Maintaining this speed, use a stopwatch to time ten revolutions. Divide the time by ten and record the period in Table 3.5.
- ⑨ Vary the mass of the object by removing the side masses. Keep the radius constant and measure the new period. Weigh the object again and record the mass and period in Table 3.5.

**Table 3.5: Varying the Mass of the Object**

Mass hanging over pulley = \_\_\_\_\_

Centripetal Force =  $mg$  = \_\_\_\_\_

Radius = \_\_\_\_\_

Mass of Object	Period (T)	Calculated Centripetal Force	% Difference

### Analysis

- ① The weight of the mass hanging over the pulley is equal to the centripetal force applied by the spring. Calculate this force by multiplying the mass hung over the pulley by “g” and record the result at the top of Table 3.5.
- ② Calculate the centripetal force for each trial using:

$$F = \frac{4\pi^2 mr}{T^2}$$

and record this in Table 3.5.

- ③ Calculate the percent difference between the calculated centripetal force for each trial and  $mg$ . Record in Table 3.5.

### Questions

- ① When the radius is increased, does the period of rotation increase or decrease?
- ② When the radius and the mass of the rotating object are held constant, does increasing the period increase or decrease the centripetal force?
- ③ As the mass of the object is increased, does the centripetal force increase or decrease?

---

***Notes:***

## **Experiment 4: Conservation of Angular Momentum Using a Point Mass**

### **EQUIPMENT REQUIRED**

- Smart Pulley Timer Program
- Rotational Inertia Accessory (ME-8953)
- Rotating Platform (ME-8951)
- Smart Pulley
- balance

### **Purpose**

A mass rotating in a circle is pulled in to a smaller radius and the new angular speed is predicted using conservation of angular momentum.

### **Theory**

Angular momentum is conserved when the radius of the circle is changed.

$$L = I_i \omega_i = I_f \omega_f$$

where  $I_i$  is the initial rotational inertia and  $\omega_i$  is the initial angular speed. So the final rotational speed is given by:

$$\omega_f = \frac{I_i}{I_f} \omega_i$$

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since  $\tau = I\alpha$ ,

$$I = \frac{\tau}{\alpha}$$

where  $\alpha$  is the angular acceleration which is equal to  $a/r$  and  $\tau$  is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where  $r$  is the radius of the cylinder about which the thread is wound and  $T$  is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass,  $m$ , gives (See Figure 4.1)

$$\Sigma F = mg - T = ma$$

Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the linear acceleration of the mass ( $m$ ) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

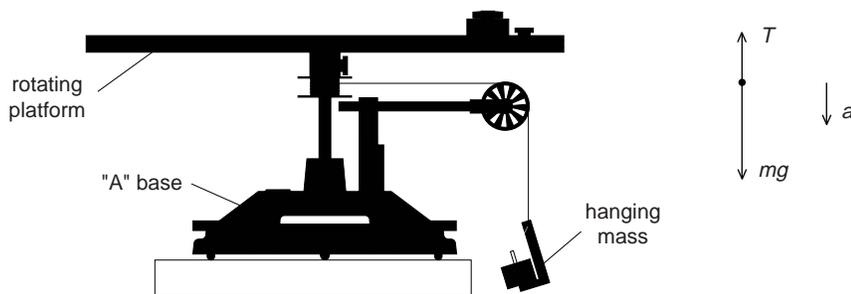


Figure 4.1: Rotational Apparatus and Free-Body Diagram

**Part I: Conservation of Angular Momentum**

**Setup**

- ① Level the apparatus using the square mass on the track as shown in the leveling instructions in the Assembly Section.
- ② Slide a thumb screw and square nut into the T-slot on the top of the track and tighten it down at about the 5 cm mark. This will act as a stop for the sliding square mass. See Figure 4.2.

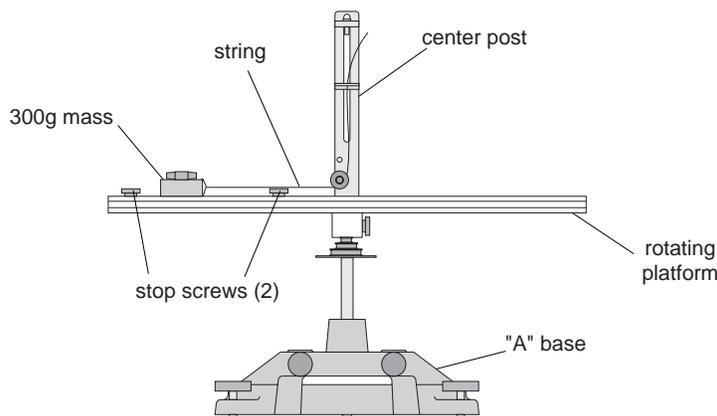


Figure 4.2: Set-up for conservation of angular momentum

- ③ With the side of the square mass that has the hole oriented toward the center post, slide the square mass onto the track by inserting its square nut into the T-slot, but do not tighten the thumb screw; the square mass should be free to slide in the T-slot.
- ④ Slide a second thumb screw and square nut into the T-slot and tighten it down at about the 20 cm mark. Now the square mass is free to slide between the two limiting stops.
- ⑤ Move the pulley on the center post to its lower position. Remove the spring bracket from the center post and set it aside.
- ⑥ Attach a string to the hole in the square mass and thread it around the pulley on the center post and pass it through the indicator bracket.
- ⑦ Mount the Smart Pulley photogate on the black rod on the base and position it so it straddles the holes in the pulley on the center rotating shaft.
- ⑧ Run the Smart Pulley Timer program.

## Procedure

- ① Select <M>-Motion Timer <RETURN>.
- ② Hold the string just above the center post. With the square mass against the outer stop, give the track a spin using your hand. After about 25 data points have been taken, pull up on the string to cause the square mass to slide from the outer stop to the inner stop.
- ③ Continue to hold the string up and take about 25 data points after pulling up on the string. Then push <RETURN> to stop the timing.
- ④ When the computer finishes calculating the times, graph the rotational speed versus time: <A>-Data Analysis Options <RETURN>; <G>-Graph Data <RETURN>; <E>-Rotational Apparatus <RETURN>; <V>-Velocity vs. Time <RETURN>.
- ⑤ After viewing the graph, press <RETURN> and choose <T> to see the table of the angular velocities. Determine the angular velocity immediately before and immediately after pulling the string. Record these values in Table 4.1.
- ⑥ Repeat the experiment a total of three times with different initial angular speeds. Record these values in Table 4.1.

**Table 4.1: Data**

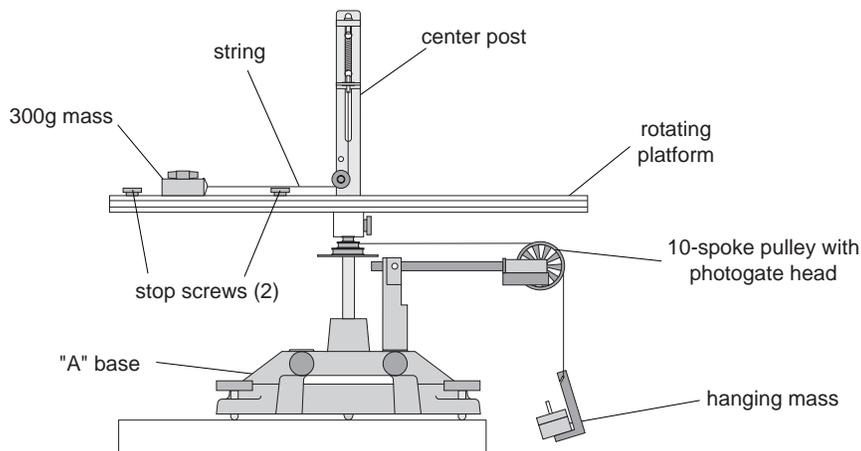
Trial Number	Angular Speeds	
	Initial	Final
1		
2		
3		

## Part II: Determining the Rotational Inertia

Measure the rotational inertia of the apparatus twice: once with the square mass in its initial position and once with it in its final position.

## Setup

- ① Attach a Smart Pulley with rod to the base using the black rod.
- ② Wind a thread around the pulley on the center shaft and pass the thread over the Smart Pulley. See Figure 4.3.



**Figure 4.3: Set-up for determining of rotational inertia**

## Procedure

### Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this “friction mass” will be subtracted from the mass used to accelerate the apparatus.

- ① To find the mass required to overcome kinetic friction run “Display Velocity”: <V>-Display Velocity <RETURN> <A>-Smart Pulley/Linear String <RETURN> <N>-Normal Display <RETURN>.
- ② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity. Record this friction mass in Table 1.4.

### Finding the Acceleration of the Apparatus

- ① To find the acceleration, put about 30 g (Record the exact hanging mass in Table 1.4) over the pulley and run “Motion Timer”: <M>-Motion Timer <RETURN>. Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.
- ② Wait for the computer to calculate the times and then press <RETURN>. To find the acceleration, graph velocity versus time: <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.
- ③ The graph will now be plotted and the  $slope = m$  will be displayed at the top of the graph. This slope is the acceleration. Push <RETURN> and <X> twice to return to the Main Menu.

### Measure Radius

- ① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record the radius in Table 4.2.

**Table 4.2 Rotational Inertia Data**

	Mass at Outer Stop	Mass at Inner Stop
Friction Mass		
Hanging Mass		
Slope		
Radius		
Rotational Inertia		

## Analysis

- ① Calculate the rotational inertia's:
  - Subtract the “friction mass” from the hanging mass used to accelerate the apparatus to determine the mass,  $m$ , to be used in the equations.
  - Calculate the experimental values of the rotational inertia and record it in Table 4.3.
- ② Calculate the expected (theoretical) values for the final angular velocity and record these values in Table 4.3.

**Table 4.3: Results**

	Trial #1	Trial #2	Trial #3
Theoretical Angular Speed			
% Difference			

- ③ For each trial, calculate the percent difference between the experimental and the theoretical values of the final angular velocity and record these in Table 4.3.

## Questions

Calculate the rotational kinetic energy  $(KE_i = \frac{1}{2}I_i\omega_i^2)$  before the string was pulled. Then calculate the rotational kinetic energy  $(KE_f = \frac{1}{2}I_f\omega_f^2)$  after the string was pulled.

Which kinetic energy is greater?

Why?

**Notes:**

## Experiment 5: Rotational Inertia of Disk and Ring

### EQUIPMENT REQUIRED

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li>- Precision Timer Program</li> <li>- Rotational Inertia Accessory (ME-9341)</li> <li>- Smart Pulley</li> <li>- calipers</li> </ul> | <ul style="list-style-type: none"> <li>- mass and hanger set</li> <li>- paper clips (for masses &lt; 1 g)</li> <li>- triple beam balance</li> </ul> |
|---|---|

### Purpose

The purpose of this experiment is to find the rotational inertia of a ring and a disk experimentally and to verify that these values correspond to the calculated theoretical values.

### Theory

Theoretically, the rotational inertia,  $I$ , of a ring about its center of mass is given by:

$$I = \frac{1}{2}M(R_1^2 + R_2^2)$$

where  $M$  is the mass of the ring,  $R_1$  is the inner radius of the ring, and  $R_2$  is the outer radius of the ring. See Figure 5.1.

The rotational inertia of a disk about its center of mass is given by:

$$I = \frac{1}{2}MR^2$$

where  $M$  is the mass of the disk and  $R$  is the radius of the disk. The rotational inertia of a disk about its diameter is given by:

$$I = \frac{1}{4}MR^2$$

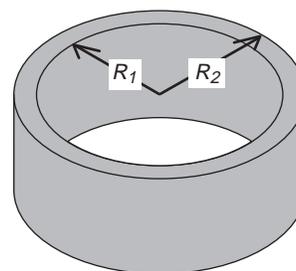
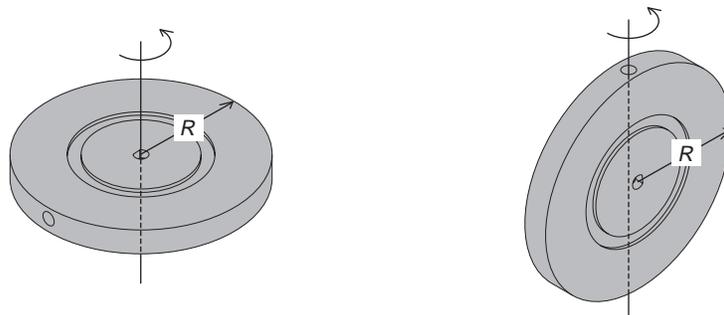


Figure 5.1: Ring



Disk about center of Mass

Disk about Diameter

Figure 5.2:

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since  $\tau = I\alpha$ ,

$$I = \frac{\tau}{\alpha}$$

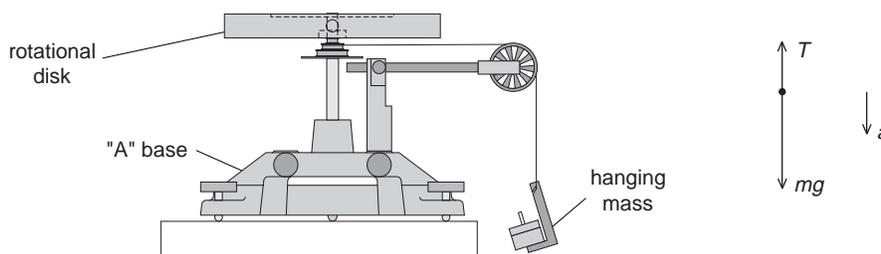
where  $\alpha$  is the angular acceleration which is equal to  $a/r$  and  $\tau$  is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where  $r$  is the radius of the cylinder about which the thread is wound and  $T$  is the tension in the thread when the apparatus is rotating.

Applying Newton's Second Law for the hanging mass,  $m$ , gives (See Figure 5.3)

$$\Sigma F = mg - T = ma$$



**Figure 5.3: Rotational Apparatus and Free-Body Diagram**

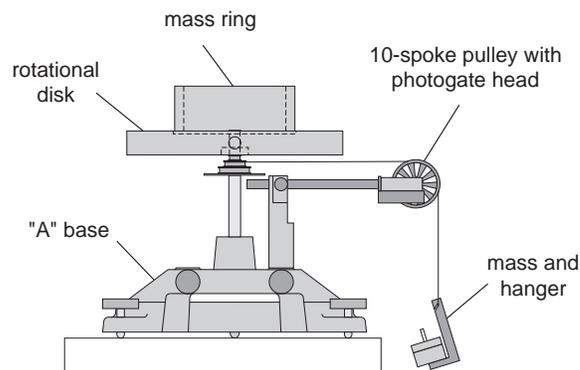
Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the linear acceleration of the mass ( $m$ ) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

### Setup

- ① Remove the track from the Rotating Platform and place the disk directly on the center shaft as shown in Figure 5.4. The side of the disk that has the indentation for the ring should be up.
- ② Place the ring on the disk, seating it in this indentation.
- ③ Mount the Smart Pulley to the base and connect it to a computer.
- ④ Run the Smart Pulley Timer program.



**Figure 5.4: Set-up for Disk and Ring**

### Procedure

#### Measurements for the Theoretical Rotational Inertia

- ① Weigh the ring and disk to find their masses and record these masses in Table 5.1.
- ② Measure the inside and outside diameters of the ring and calculate the radii  $R_1$  and  $R_2$ . Record in Table 5.1.
- ③ Measure the diameter of the disk and calculate the radius  $R$  and record it in Table 5.1.

**Table 5.1: Theoretical Rotational Inertia**

Mass of Ring	
Mass of Disk	
Inner Radius of Ring	
Outer Radius of Ring	
Radius of Disk	

## Measurements for the Experimental Method

### Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this “friction mass” will be subtracted from the mass used to accelerate the ring.

- ① To find the mass required to overcome kinetic friction run “Display Velocity”: <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.
- ② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity. Record the friction mass in Table 5.2.

**Table 5.2: Rotational Inertia Data**

	Ring and Disk Combined	Disk Alone	Disk Vertical
Friction Mass			
Hanging Mass			
Slope			
Radius			

### Finding the Acceleration of Ring and Disk

- ① To find the acceleration, put about 50 g over the pulley and run “Motion Timer”: <M>-Motion Timer <RETURN> Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.
- ② Wait for the computer to calculate the times and then press <RETURN>. To find the acceleration, graph velocity versus time: <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN>.
- ③ The graph will now be plotted and the slope =  $m$  will be displayed at the top of the graph. This slope is the acceleration. Record in Table 5.2.
- ④ Push <RETURN> and <X> twice to return to the Main Menu.

### Measure the Radius

- Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record in Table 5.2.

### Finding the Acceleration of the Disk Alone

Since in **Finding the Acceleration of Ring and Disk** the disk is rotating as well as the ring, it is necessary to determine the acceleration, and the rotational inertia, of the disk by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the ring.

- To do this, take the ring off the rotational apparatus and repeat **Finding the Acceleration of Ring and Disk** for the disk alone.

► **NOTE:** that it will take less “friction mass” to overcome the new kinetic friction and it is only necessary to put about 30 g over the pulley in **Finding the Acceleration of Ring and Disk**.

### Disk Rotating on an Axis Through Its Diameter

Remove the disk from the shaft and rotate it up on its side. Mount the disk vertically by inserting the shaft in one of the two “D”-shaped holes on the edge of the disk. See Figure 5.5.

► **WARNING!** Never mount the disk vertically using the adapter on the track. The adapter is too short for this purpose and the disk might fall over while being rotated.

Repeat steps **Measure the Radius** and **Finding the Acceleration of the Disk Alone** to determine the rotational inertia of the disk about its diameter. Record the data in Table 5.2.

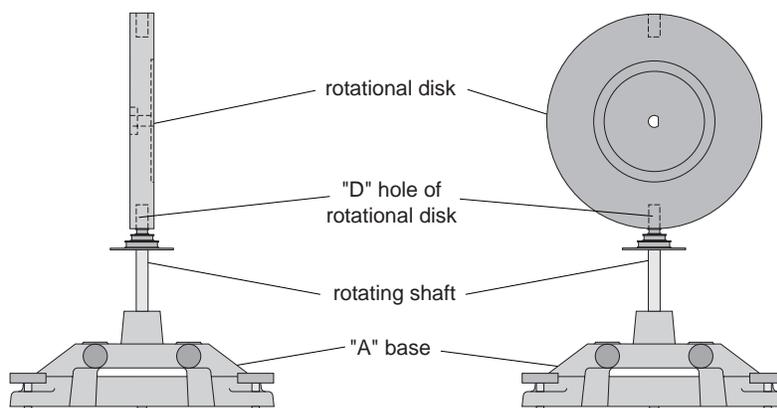


Figure 5.5: Disk mounted vertically

### Calculations

Record the results of the following calculations in Table 5.3.

- Subtract the “friction mass” from the hanging mass used to accelerate the apparatus to determine the mass,  $m$ , to be used in the equations.
- Calculate the experimental value of the rotational inertia of the ring and disk together.
- Calculate the experimental value of the rotational inertia of the disk alone.
- Subtract the rotational inertia of the disk from the total rotational inertia of the ring and disk.

This will be the rotational inertia of the ring alone.

- ⑤ Calculate the experimental value of the rotational inertia of the disk about its diameter.
- ⑥ Calculate the theoretical value of the rotational inertia of the ring.
- ⑦ Calculate the theoretical value of the rotational inertia of the disk about its center of mass and about its diameter.
- ⑧ Use a percent difference to compare the experimental values to the theoretical values.

**Table 5.3: Results**

Rotational Inertia for Ring and Disk Combined	
Rotational Inertia for Disk Alone (experimental value)	
Rotational Inertia for Ring (experimental value)	
Rotational Inertia for Vertical Disk (experimental value)	
Rotational Inertia for Disk (theoretical value)	
Rotational Inertia for Ring (theoretical value)	
Rotational Inertia for Vertical Disk (theoretical value)	
% Difference for Disk	
% Difference for Ring	
% Difference for Vertical Disk	

**Notes:**

## **Experiment 6: Rotational Inertia of Disk Off-Axis (Fixed/Rotating)**

### **EQUIPMENT REQUIRED**

- |  |                                  |
|--|----------------------------------|
| - Precision Timer Program                | - mass and hanger set            |
| - Rotational Inertia Accessory (ME-8953) | - paper clips (for masses < 1 g) |
| - Smart Pulley                           | - triple beam balance            |
| - calipers                               |                                  |

### **Purpose**

The purpose of this experiment is to find the rotational inertia of a disk about an axis parallel to the center of mass axis.

### **Theory**

Theoretically, the rotational inertia,  $I$ , of a disk about a perpendicular axis through its center of mass is given by:

$$I_{cm} = \frac{1}{2} MR^2$$

where  $M$  is the mass of the disk and  $R$  is the radius of the disk. The rotational inertia of a disk about an axis parallel to the center of mass axis is given by:

$$I = I_{cm} + Md^2$$

where  $d$  is the distance between the two axes.

In one part of this experiment, the disk is mounted on its ball bearing side which allows the disk to freely rotate relative to the track. So as the track is rotated, the disk does not rotate relative to its center of mass. Since the disk is not rotating about its center of mass, it acts as a point mass rather than an extended object and its rotational inertia reduces from:

$$I = I_{cm} + Md^2 \text{ to } I = Md^2$$

To find the rotational inertia experimentally, a known torque is applied to the object and the resulting angular acceleration is measured. Since  $\tau = I\alpha$ ,

$$I = \frac{\tau}{\alpha}$$

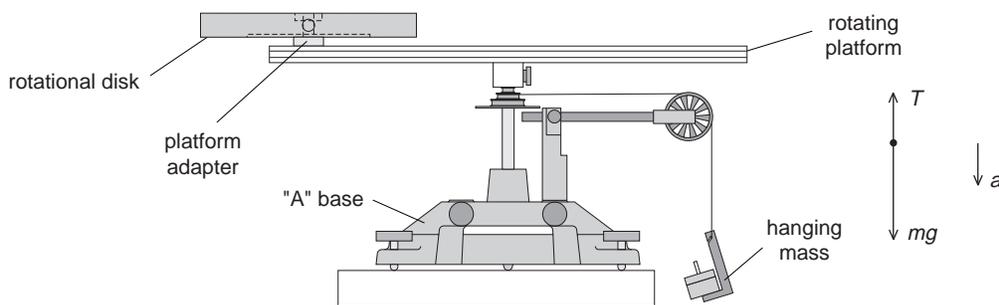
where  $\alpha$  is the angular acceleration which is equal to  $a/r$  and  $\tau$  is the torque caused by the weight hanging from the thread which is wrapped around the base of the apparatus.

$$\tau = rT$$

where  $r$  is the radius of the cylinder about which the thread is wound and  $T$  is the tension in the thread when the apparatus is rotating.

Applying Newton’s Second Law for the hanging mass,  $m$ , gives (See Figure 6.1)

$$\Sigma F = mg - T = ma$$



**Figure 6.1: Rotational Apparatus and Free-Body Diagram**

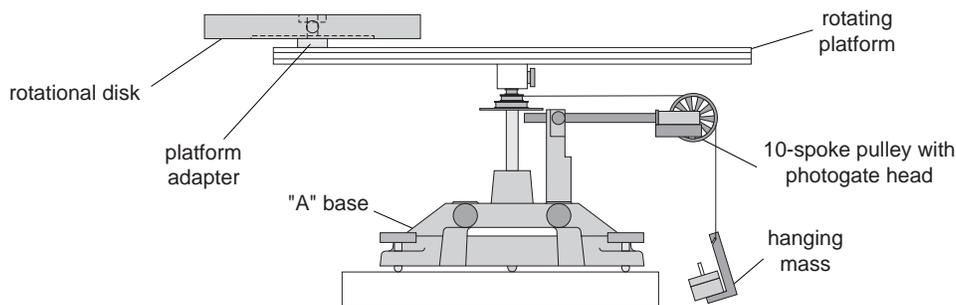
Solving for the tension in the thread gives:

$$T = m(g - a)$$

Once the linear acceleration of the mass ( $m$ ) is determined, the torque and the angular acceleration can be obtained for the calculation of the rotational inertia.

**Setup**

- ① Set up the Rotational Accessory as shown in Figure 6.2. Mount the disk with its bearing side up. Use the platform adapter to fasten the disk to the track at a large radius.



**Figure 6.2: Set-up for Disk Off-Axis**

- ② Mount the Smart Pulley to the base and connect it to a computer.
- ③ Run the Smart Pulley Timer program.

**Measurements For the Theoretical Rotational Inertia**

Record these measurements in Table 6.1.

- ① Weigh the disk to find the mass  $M$ .
- ② Measure the diameter and calculate the radius  $R$ .
- ③ Measure the distance,  $d$ , from the axis of rotation to the center of the disk.

**Table 6.1: Theoretical Rotational Inertia**

Mass of Disk	
Radius of Disk	
Distance Between Parallel Axis	

## Measurements For the Experimental Method

### Accounting For Friction

Because the theory used to find the rotational inertia experimentally does not include friction, it will be compensated for in this experiment by finding out how much mass over the pulley it takes to overcome kinetic friction and allow the mass to drop at a constant speed. Then this “friction mass” will be subtracted from the mass used to accelerate the ring.

- ① To find the mass required to overcome kinetic friction run “Display Velocity”: <V>-Display Velocity <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <N>-Normal Display <RETURN>.
- ② Put just enough mass hanging over the pulley so that the velocity is constant to three significant figures. Then press <RETURN> to stop displaying the velocity. Record the friction mass in Table 6.2.

### Finding the Acceleration of Disk and Track

**Table 6.2: Rotational Inertia Data**

	Fixed Disk and Track Combined	Track Alone	Rotating Disk and Track Combined
Friction Mass			
Hanging Mass			
Slope			
Radius			

- ① To find the acceleration, put about 50 g over the pulley and run “Motion Timer”: <M>-Motion Timer <RETURN>. Wind the thread up and let the mass fall from the table to the floor, hitting <RETURN> just before the mass hits the floor.
- ② Wait for the computer to calculate the times and then press <RETURN>. To find the acceleration, graph velocity versus time: <G>-Graph Data <RETURN>; <A>-Smart Pulley/Linear String <RETURN>; <V>-Velocity vs. Time <R>-Linear Regression <SPACEBAR> (toggles it on) <S>-Statistics <SPACEBAR> <RETURN> The graph will now be plotted and the *slope* =  $m$  will be displayed at the top of the graph. This slope is the acceleration. Push <RETURN> and <X> twice to return to the Main Menu. Record this slope in Table 6.2.

### Measure the Radius

- ① Using calipers, measure the diameter of the cylinder about which the thread is wrapped and calculate the radius. Record in Table 6.2.

### Finding the Acceleration of Track Alone

Since in **Finding the Acceleration of Disk and Track** the track is rotating as well as the disk, it is necessary to determine the acceleration, and the rotational inertia, of the track by itself so this rotational inertia can be subtracted from the total, leaving only the rotational inertia of the disk.

- ① To do this, take the disk off the rotational apparatus and repeat **Finding the Acceleration of Disk and Track** for the track alone.

◆ **NOTE:** It will take less “friction mass” to overcome the new kinetic friction and it is only necessary to put about 30 g over the pulley in **Finding the Acceleration of Disk and Track**.

### Disk Using Ball Bearings (Free Disk)

Mount the disk upside-down at the same radius as before. Now the ball bearings at the center of the disk will allow the disk to rotate relative to the track. Repeat **Accounting For Friction** and **Finding the Acceleration of Disk and Track** for this case and record the data in Table 6.2.

### Calculations

Record the results of the following calculations in Table 6.3.

- ① Subtract the “friction mass” from the hanging mass used to accelerate the apparatus to determine the mass,  $m$ , to be used in the equations.
- ② Calculate the experimental value of the rotational inertia of the fixed disk and track combined.
- ③ Calculate the experimental value of the rotational inertia of the track alone.
- ④ Subtract the rotational inertia of the track from the rotational inertia of the fixed disk and track. This will be the rotational inertia of the fixed disk alone.
- ⑤ Calculate the experimental value of the rotational inertia of the fixed disk and track combined.
- ⑥ Subtract the rotational inertia of the track from the rotational inertia of the free disk and track. This will be the rotational inertia of the free disk alone.
- ⑦ Calculate the theoretical value of the rotational inertia of the fixed disk off axis.

**Table 6.3: Results**

Rotational Inertia for Fixed Disk and Track Combined	
Rotational Inertia for Track Alone	
Rotational Inertia for Fixed Disk Off-Axis (experimental value)	
Rotational Inertia for Free Disk and Track Combined	
Rotational Inertia for Free Disk Alone (experimental value)	
Rotational Inertia for Fixed Disk Off-Axis (theoretical value)	
Rotational Inertia for Point Mass (theoretical value)	
% Difference for Fixed	
% Difference for Free Disk	

- ⑧ Calculate the theoretical value of a point mass having the mass of the disk.
- ⑨ Use a percent difference to compare the experimental values to the theoretical values.

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**Notes:**

## Experiment 7: Conservation of Angular Momentum

### EQUIPMENT REQUIRED

- Smart Pulley Timer Program - balance
- Rotational Inertia Accessory (ME-8953)
- Rotating Platform (ME-8951)
- Smart Pulley Photogate

### Purpose

A non-rotating ring is dropped onto a rotating disk and the final angular speed of the system is compared with the value predicted using conservation of angular momentum.

### Theory

When the ring is dropped onto the rotating disk, there is no net torque on the system since the torque on the ring is equal and opposite to the torque on the disk. Therefore, there is no change in angular momentum. Angular momentum is conserved.

$$L = I_i \omega_i = I_f \omega_f$$

where  $I_i$  is the initial rotational inertia and  $\omega_i$  is the initial angular speed. The initial rotational inertia is that of a disk

$$\left(\frac{1}{2}\right) M_1 R^2$$

and the final rotational inertia of the combined disk and ring is

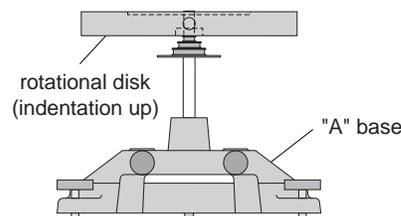
$$I_f = \frac{1}{2} M_1 R^2 + \frac{1}{2} M_2 (r_1^2 + r_2^2)$$

So the final rotational speed is given by

$$\omega_f = \frac{M_1 R^2}{M_1 R^2 + M_2 (r_1^2 + r_2^2)} \omega_i$$

### Setup

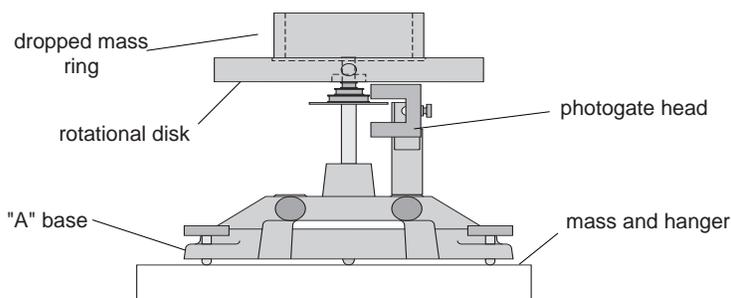
- ① Level the apparatus using the square mass on the track.
- ② Assemble the Rotational Inertia Accessory as shown in Figure 7.1. The side of the disk with the indentation for the ring should be up.
- ③ Mount the Smart Pulley photogate on the black rod on the base and position it so it straddles the holes in the pulley on the center rotating shaft.
- ④ Run the Smart Pulley Timer program.



**Figure 7.1: Assembly for Dropping Ring onto Disk**

### Procedure

- ① Select <M>-Motion Timer <RETURN>.
- ② Hold the ring just above the center of the disk. Give the disk a spin using your hand. After about 25 data points have been taken, drop the ring onto the spinning disk See Figure 7.2.



**Figure 7.2: Experiment Setup**

- ③ Continue to take data after the collision and then push <RETURN> to stop the timing.
- ④ When the computer finishes calculating the times, graph the rotational speed versus time. <A>-Data Analysis Options <RETURN> <G>-Graph Data <RETURN> <E>-Rotational Apparatus <RETURN> <V>-Velocity vs. Time <RETURN>
- ⑤ After viewing the graph, press <RETURN> and choose <T> to see the table of the angular velocities. Determine the angular velocity immediately before and immediately after the collision. Record these values in Table 7.1.
- ⑥ Weigh the disk and ring and measure the radii. Record these values in Table 7.1.

### Analysis

**Table 7.1: Data and Results**

- ① Calculate the expected (theoretical) value for the final angular velocity and record this value in Table 7.1.
- ② Calculate the percent difference between the experimental and the theoretical values of the final angular velocity and record in Table 7.1.

Initial Angular Speed	
Final Angular Speed (experimental value)	
Mass of Disk	
Mass of Ring	
Inner Radius of Ring	
Outer Radius of Ring	
Radius of Disk	
Final Angular Speed (theoretical value)	
% Difference Between Final Angular Speeds	

## Questions

- ① Does the experimental result for the angular speed agree with the theory?
- ② What percentage of the rotational kinetic energy lost during the collision? Calculate this and record the results in Table 7.1.

$$\%KE \text{ Lost} = \frac{\frac{1}{2}I_i\omega_i^2 - \frac{1}{2}I_f\omega_f^2}{\frac{1}{2}I_i\omega_i^2}$$

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**Notes:**

# Technical Support

## Feed-Back

If you have any comments about this product or this manual please let us know. If you have any suggestions on alternate experiments or find a problem in the manual please tell us. PASCO appreciates any customer feed-back. Your input helps us evaluate and improve our product.

## To Reach PASCO

For Technical Support call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

email: [techsupp@PASCO.com](mailto:techsupp@PASCO.com)

Tech support fax: (916) 786-3292

## Contacting Technical Support

Before you call the PASCO Technical Support staff it would be helpful to prepare the following information:

- If your problem is computer/software related, note:

Title and Revision Date of software.

Type of Computer (Make, Model, Speed).

Type of external Cables/Peripherals.

- If your problem is with the PASCO apparatus, note:

Title and Model number (usually listed on the label).

Approximate age of apparatus.

A detailed description of the problem/sequence of events. (In case you can't call PASCO right away, you won't lose valuable data.)

If possible, have the apparatus within reach when calling. This makes descriptions of individual parts much easier.

- If your problem relates to the instruction manual, note:

Part number and Revision (listed by month and year on the front cover).

Have the manual at hand to discuss your questions.

