Centripetal Force Apparatus
(Order Code CFA)

The Centripetal Force Apparatus (CFA) facilitates the study of circular motion. It allows students to easily and accurately see the relationship between centripetal force, tangential velocity (or angular velocity), radius and mass. The traditional method, i.e., twirling a rubber stopper in a horizontal circle, is instructional in that students can have kinesthetic understanding of the relationships. For example, they can feel the change in the force as the radius changes. The CFA allows students to make direct measurements of the variables and to obtain excellent quantitative data.

With this equipment, students are able to investigate relationships between

- Centripetal force and the mass of the accelerating object
- Centripetal force and the radius of the motion
- Centripetal force and the tangential velocity of the accelerating object
- Centripetal force and the angular velocity of the accelerating object
- Angular acceleration, torque and moment of inertia

## What is included with the Centripetal Force Apparatus?

- Rectangular Frame
- Support Legs (2)
- Rotating Assembly consisting of Rotational Shaft, Encoder Wheel, 3-Step Pulley, Rotating Beam, Bearing Housing
- Sliding Carriage to hold the test masses
- Counterbalance Carriage to balance the rotating beam
- Swivel Assembly (connects Sliding Carriage to a Dual-Range Force Sensor)
- Ultra Pulley
- Ultra Pulley Bracket (preinstalled on Assembly)
- Photogate Bracket with 1/4 x 20 mounting screw (preinstalled on Assembly)
- Dual-Range Force Sensor Bracket (preinstalled on Assembly)
- 50 g masses (2)
- 100 g masses (4)
- Hook (attaches a Wireless Dynamic Sensor System (WDSS) to the Sliding Carriage)
- WDSS Mounting Screw and T Nut to secure a WDSS

## A Closer Look at the Components

Rectangular Frame
The frame supports the Rotating Assembly and it accommodates a variety of sensors. Two Pulley Guides on the top of the frame allow a Dual-Range Force Sensor to be connected to a carriage that slides along the Rotating Beam.
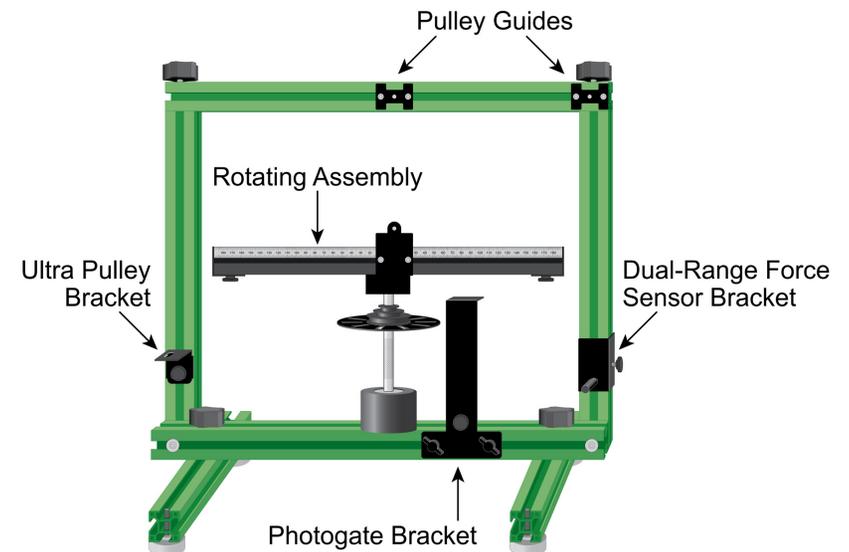
Rotating Assembly

The Rotating Assembly consists of a Rotating Beam, Rotational Shaft, Bearing Housing, Encoder Wheel, and 3-Step Pulley. Carriages are placed on the Rotating Beam. A string can be attached to the 3-Step Pulley to apply a torque to the Rotational Shaft.

In the middle of the Rotating Beam, you'll find a Pulley Guide. A string from a Dual-Range Force Sensor threaded through this pulley can be used to attach the force sensor to the Sliding Carriage.
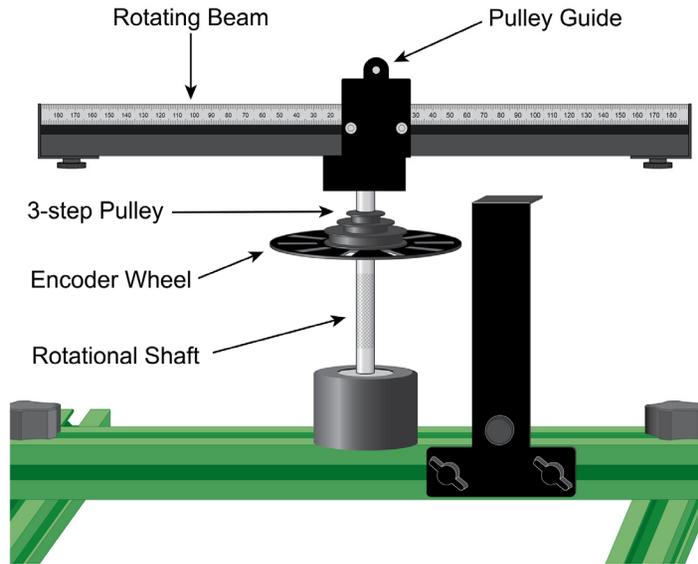

Carriages

Two carriages ride on the Rotating Beam during data collection. A Sliding Carriage (shown at left) has low friction bearings that allow it to slide along the beam during the experiment. The Sliding Carriage is attached to a force sensor (e.g., a Dual-Range Force Sensor or Wireless Dynamic Sensor System). A Counterbalance Carriage (shown at right) is secured to the other side of the beam using screws and T-nuts. As the beam rotates, the force sensor measures the centripetal force on the Sliding Carriage. A separate sensor (i.e., a Vernier Photogate) measures the angular position and angular velocity.

Swivel Assembly

The Swivel Assembly consists of two strings and a swivel. The assembly is used to connect the Sliding Carriage to a Dual-Range Force Sensor. A small screw on one end of the assembly connects to the end of the force sensor. The other end of the Swivel Assembly contains a loop that slides over a hook on the Sliding Carriage.
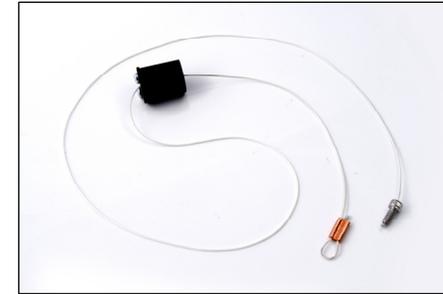
Swivel Assembly

Dual-Range Force Sensor Bracket

This bracket is attached to the right side of the frame. Slide the Dual-Range Force Sensor onto the post and use the plastic 1/4 x 20 screw that ships with the force sensor to secure the sensor to the bracket. A screw on the right side of the bracket allows the bracket to move up and down, which enables a change in the radius of motion of the Sliding Carriage when attached via the Swivel Assembly.

Photogate Bracket

This bracket, located on the bottom of the frame, allows you to attach a Vernier Photogate to the frame. A 1/4 x 20 screw is stored in the bottom of the bracket.

Ultra Pulley and Pulley Bracket

The Ultra Pulley and Pulley Bracket allow a torque to be applied to the Rotational Shaft. Secure the Ultra Pulley to the bracket using the included 1/4 x 20 screw. Attach one end of a string to the 3-Step Pulley mounted on the Rotational Shaft. Attach a small mass to the other end of the string. Run the string over the Ultra Pulley and allow it to fall to apply a torque to the Rotational Shaft.

Ultra Pulley   *Ultra Pulley Bracket*

WDSS Screw and Clip

The WDSS Screw allows you to attach the WDSS to the rotating beam. The Clip connects the WDSS to the hook on the Sliding Carriage.

Masses

Two 50 g masses and four 100 g masses are included in the apparatus. They slip into the carriages to allow you to vary the masses of the carriages.

Assembly and Storage of the Frame and Support Legs

The apparatus is shipped flat, and it can be stored flat when not in use. The Rotating Assembly and Rectangular Frame come completely assembled. The brackets for the Dual-Range Force Sensor, Vernier Photogate, and Vernier Ultra Pulley are also preinstalled. The Support Legs are stored on the sides of the frame. Remove the knob of the knob screw that holds each leg and use the knob screw to attach each Support Leg to the bottom of the frame, then replace the knob and tighten. Reverse this procedure to store the equipment.

Rectangular Frame stored flat. Support legs attached to the underside of the side vertical frame members.

Leveling the Apparatus

Follow these steps to level the apparatus.

1. Secure the Counterbalance Carriage to the outer end of the Rotating Beam.
2. Place 250 grams of mass in the carriage. **WARNING:** Using more than 250 grams of mass in a mass carriage may result in the top mass ejecting at high speed.
3. Use a flathead screw driver to lower each foot on the CFA footer to its lowest height.
4. Give the Rotating Beam a very slow spin and watch its motion. The beam will tend to settle to its lowest point. Confirm the location of lowest point by spinning the beam a couple more times.
5. Raise the lowest end or side of the apparatus by increasing the height of the nearby footer or footers.
6. Repeat Steps 4 and 5 until the beam spins without returning to a consistently low spot.

WARNING: Always wear safety glasses when using the Centripetal Force Apparatus to prevent injury from the rotating beam.

Attaching the Carriages to the Rotating Beam

It is important to attach the carriages in the proper orientation on the Rotating Beam. The beam is not symmetric about the Pulley Guide located near the middle of the beam. With the ruled side of the rotating beam facing you, the Sliding Carriage goes on the right and the Counterbalance Carriage goes on the left.
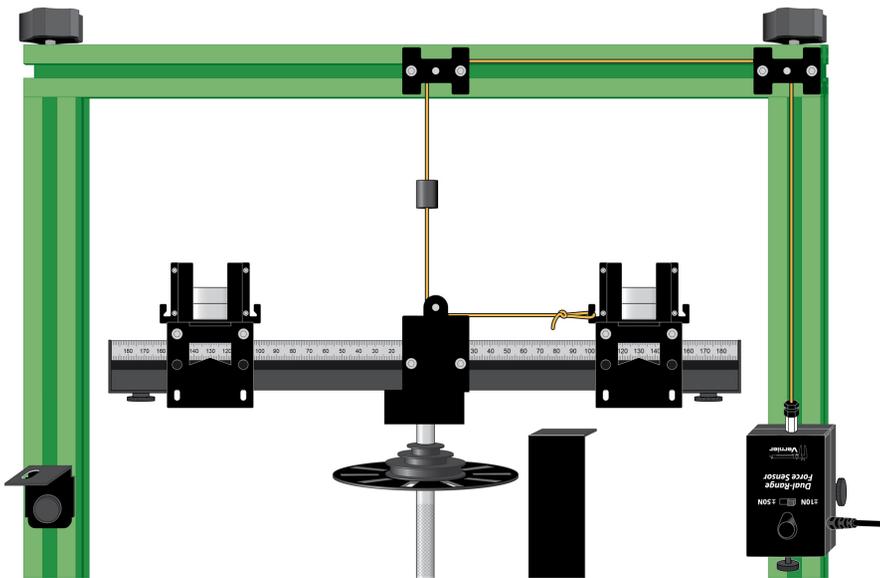
Counterbalance Carriage on left. Sliding Carriage on right.

To attach the carriages, remove the end pieces on the Rotating Beam. As you look at the ruled side of the Rotating Beam, you will attach the Sliding Carriage to the right side as follows:

1. Note the sets of bearings upon which the carriage slides. Two sets of bearings appear on the top of the carriage and one set appears on the bottom.

2. As you slide the Sliding Carriage on the beam, orient the carriage so that the end of the carriage with the single bottom set of bearings slides on first. (See on next page.) If you orient the carriage the other way, your carriage will not be able to reach its maximum radius (~16 cm) on the beam.

3. Slide the Counterbalance Carriage on the other side of the beam.

WARNING: Always wear safety glasses when using the Centripetal Force Apparatus to prevent injury from the rotating beam.
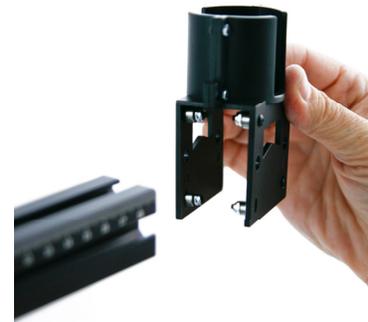
*Attaching the Sliding Carriage to the Rotating Beam*

Using Sensors with the Apparatus

While investigating centripetal force with this apparatus, students use sensors to measure force and angular velocity. *Our recommendation is to use the Dual-Range Force Sensor to measure force and the Vernier Photogate to measure angular speed.* The Vernier Wireless Dynamic Sensor System can also be used to measure force. The following describes how to connect each sensor to the apparatus.

Attaching a Dual-Range Force Sensor to the Frame

A Dual-Range Force Sensor attaches to the right-hand vertical side of the apparatus. Follow these assembly instructions.

1. In normal use, a hook or a bumper is attached to the end of the Dual-Range Force Sensor. Remove the hook or bumper if it is attached.

2. Two pulleys are attached to the top of the frame. With the pulleys facing you, attach the Dual-Range Force Sensor to the Force Sensor Bracket on the right side.

3. Thread the screw end of the Swivel Assembly over the middle pulley on the top of the frame, then thread the screw end through the pulley on the right side of the frame.

4. Attach the screw end of the Swivel Assembly to the force sensor, as shown below.

5. Thread the loop end of the Swivel Assembly under the Pulley Guide near the middle of the beam and attach the loop end to the Sliding Carriage, as shown in the larger photo on page 7. The Sliding Carriage should be on the right side of the Rotating Beam with the ruled side of the beam facing you.
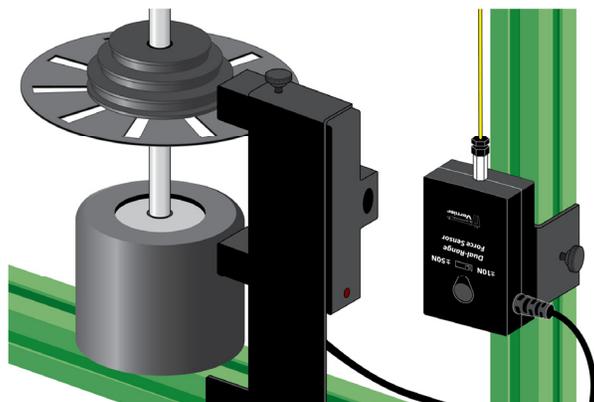
Dual-Range Force Sensor attached to frame, and with screw end of Swivel Assembly attached. Vertical adjustment screw on the right.

Attaching a Photogate

A photogate can be attached to the Vernier Photogate Bracket, which is positioned next to the Encoder mounted on the Rotating Shaft. Follow these assembly instructions:

1. Locate the Photogate Bracket on the lower horizontal piece of the frame.
2. Secure the photogate into the stand with the 1/4 x 20 mounting screw. In this position the photogate beam will be interrupted by the Encoder Wheel.

Attaching a Wireless Dynamic Sensor System (WDSS)

The WDSS can be used instead of the Dual-Range Force Sensor, and attaches to the horizontal rotating beam. Follow these assembly instructions:

1. On the middle of the Rotating Beam, you'll find a Pulley Guide used when the Swivel Assembly is connected to the Dual-Range Force Sensor. Loosen the wing nuts on the pulley and remove them from the beam.
2. Attach the Sliding Carriage to the Rotating Beam if it is not already attached.
3. Remove the end piece and the Counterbalance Carriage if it is mounted on the Rotating Beam.
4. Attach the WDSS mounting screw and T-nut to the WDSS, slide the WDSS onto the Rotating Beam so that the hook end is adjacent to the Sliding Carriage.
5. Attach the small end of the WDSS clip to the hook end of the WDSS.
6. Clip the other end of the WDSS clip to the Sliding Carriage.
7. Move the Sliding Carriage to the desired radius. Pull the WDSS tight and secure it to the beam with its mounting screw.

Removable Pulley Guide on Rotating Beam

WDSS attached to beam and Sliding Carriage

Note: The beam is not perfectly balanced when using a WDSS, because the Counterbalance Carriage cannot be placed directly opposite the Sliding Carriage. The shaft and bearing are sufficiently rigid such that a small imbalance will not affect results.

Data-Collection Interface and Software Compatibility

Data collection with the CFA is possible with the following combinations of interfaces and software.

- **Logger *Pro* 3** Use this computer program with LabQuest® 2, LabQuest, LabQuest Mini, and LabPro®.
- **LabQuest App** Use this program with LabQuest 2 or original LabQuest, when LabQuest 2 or original LabQuest is used as a standalone device.
- **DataQuest App** Use this application with TI-Nspire™ Technology and the TI-Nspire™ Lab Cradle.
- **LabVIEW™** National Instruments LabVIEW™ software is a graphical programming language sold by National Instruments. It is used with SensorDAQ and the sensors that are compatible with the CFA. Contact Vernier for more information concerning compatibility.

Data-Collection Overview and Software Setup

Sensors used with the CFA provide a reading of the force required to keep the Sliding Carriage in position (the centripetal force) and the angular speed of the rotating beam. Data can be collected from both sensors simultaneously, but the software data-collection mode choices will depend on your goals and the particular sensors chosen.

In order to discuss common data-collection modes used with this apparatus, let us first examine a few experiments for context.

Experiments fall into two broad classes: exploration of centripetal force relations ($F=mv^2/r$, where v is the tangential velocity, or $F=mr\omega^2$, where ω is the angular velocity) and moment of inertia experiments. We will concentrate here on centripetal force.

Although the v^2/r relationship is commonly encountered first in a physics curriculum, the basic sensor measurement is angular speed. As a result, any software configuration that reports tangential velocity will be more complex to implement, because the student must provide the additional radius information in order for the software to calculate tangential velocity from angular velocity ($v=\omega r$). We recommend the use of angular velocity for analysis with this apparatus.

Another data-collection subtlety is the behavior of photogate-based data collection compared to time-based data collection. Most often with sensors, data collection is time-based, where the sensor value is recorded at uniform time intervals, such as every 0.02 seconds, or 50 times per second. Photogate data collection, in contrast, is a record of times at which the gate state changes. These times will not be at regular time intervals.

If force data are taken whenever the photogate records a transition (known as Digital Events mode in Logger *Pro*), data will not be uniformly spaced. For most analyses, unevenly spaced points will not matter. If force data are collected at uniform time intervals, either the force or velocity data will have to be interpolated in order to create a graph of force *vs.* velocity or velocity^2.

Different combinations of sensors and interfaces will determine how data are best collected. The Photogate always yields event times, even if other data collection is in time-based mode. The WDSS and the Dual-Range Force Sensor can be used in either time- or event-based data collection on LabQuest, but on Logger *Pro* the WDSS must be used in time-based data collection.

The following sections give setup suggestions for a single experiment, centripetal force *vs.* velocity (or velocity^2), using various sensor combinations, interfaces, and either the angular velocity or the much simpler tangential velocity approach. We suggest that you begin with one of our Logger *Pro* experiment files available in the Probes and Sensors folder in Logger *Pro* version 3.8.5.1 and later.

Angular Velocity – Logger *Pro* 3 with Dual-Range Force Sensor and Vernier Photogate

Open the file CFA-DFS-Photogate-angular.cmbl. This file is set up for a Dual-Range Force Sensor and a Vernier Photogate. The file contains the setup and a few calculated columns that allow for easy data collection. The data-collection mode is time-based, which means that the force readings will be taken at a 50 Hz rate, and the photogate readings will happen as the Encoder Wheel rotates. As a result, the force readings are blank when there is a velocity reading, and vice versa. This prevents direct graphing of these columns, until a simple calculation is done to provide interpolated force values between the regularly-spaced values.

	Time (s)	Force (N)	Distance (rad)	Velocity (rad/s)	ω^2 (s^{-2})	F–i (N)
1	0.00000	5.691				5.691
2	0.00684		0.000			5.693
3	0.02000	5.697				5.697
4	0.03156					5.701
5	0.04000	5.703				5.703
6	0.04057		0.628	18.555	344.3	5.702
7	0.06000	5.661				5.661
8	0.06547					5.658
9	0.07453		1.256	18.499	342.2	5.652
10	0.08000	5.649				5.649
11	0.09943					5.661
12	0.10000	5.661				5.661
13	0.10846		1.884	18.471	341.2	5.640
14	0.12000	5.612				5.612
15	0.13343					5.596
16	0.14000	5.588				5.588

The column labeled "Force" contains the raw sensor values. The calculated column "Force Interpolated," or "F-i" for short, fills in the missing values. To see how we defined the column, hover your mouse over the F-i column header in the data table to see the definition. Any graphs between force and velocity must use the F-i column.

The photogate is used to collect motion data of the object, where the "Distance" column increments by a fixed amount for each block-to-block pair sensed by the gate. Since the Encoder Wheel has ten slots, the increment is set to 0.628, with units of radians, or $2\pi/10$. The velocity (ω) column then has units of radians/second.

The file also contains a calculated column called "angular velocity^2," or ω^2 for short. This column is helpful in the data analysis, since a graph of F *vs.* ω^2 is a direct proportionality of slope mr, given that $F=mr\omega^2$.

Connect an interface, Vernier Photogate, and Dual-Range Force Sensor, and reopen the file CFA-DFS-Photogate-angular.cmbl. Place equal masses on the Sliding Carriage and Counterbalance Carriage. Adjust the location of the force sensor so that the Sliding Carriage will move in a circle of about a 10 cm radius, and set the Counterbalance Carriage to a similar radius.

The current force reading is shown in the Logger *Pro* live readout. Spin the beam so that the force reaches a reading of more than 5 N. This is most easily done by spinning the shaft between the thumb and fingers. Start data collection.

Observe the Force-Interpolated *vs.* Time graph, and then display Force-Interpolated *vs.* Angular Velocity. Also create and analyze a graph of Force-Interpolated *vs.* Angular Velocity^2.

Your graphs show how centripetal force varies with angular velocity. Now take additional data with other masses and other radii.

Angular Velocity – LabQuest App with Dual-Range Force Sensor and Vernier Photogate

Data collection with the Dual-Range Force Sensor and Vernier Photogate is simplified because the LabQuest App automatically calculates the interpolated force. To find the angular velocity, you must configure the photogate motion timing mode with the angular position information, detailed below.

1. Start the LabQuest App and let it auto-ID the sensors.
2. On the Meter tab of the LabQuest App, tap Mode.
3. Tap User Defined.
4. Enter 1/10 of the angular position change for each slot, or $2\pi/10$, as the User Defined value. You will not need to adjust this value each time you change the radius, since the angular velocity is independent of radius.
5. On this screen, choose the option to end the data collection with the Stop button.
6. Tap OK.

Collect data and examine the graphs. For further analysis, change one of your graphs to display Force *vs.* Velocity or Force *vs.* Velocity^2.

Tangential Velocity – Logger *Pro* 3 with Dual-Range Force Sensor and Vernier Photogate

If desired, you can add calculations to the Logger *Pro* file to determine the tangential velocity, and use that quantity instead of angular velocity for graphs. We show you how to add these calculations in the file CFA-DFS-Photogate-tangential.cmbl. This file is set up for Dual-Range Force Sensor and a Vernier Photogate, and provides several calculated columns.

The first is the same interpolated force column as in the example above.

The second calculation is needed to determine tangential velocity, since the tangential velocity of the rotating mass is a function of its radius of motion, using $v=\omega r$. The photogate is set up as before to collect motion data, and the "Tangential Velocity" column is used to find the product of the angular velocity and the current radius. The file contains a User Parameter called "Radius." The student must set the parameter to match the radius of motion for each run. Take note that if the parameter is changed for a later run, all columns depending on this parameter will be updated. This includes stored runs, therefore, altering the radius may upset previous calculations, including curve fits.

After taking data as before, observe the Force-Interpolated *vs.* Time graph, and then display Force-Interpolated *vs.* Tangential Velocity. Also create and analyze a graph of Force-Interpolated *vs.* Velocity^2.

Your graphs show how centripetal force varies with tangential velocity. Now take additional data with other masses and other radii. The slope of the line for the velocity^2 graph will be proportional to mass, and inversely proportional to radius, per $F=mv^2/r$.

Tangential Velocity – LabQuest App with Dual-Range Force Sensor and Vernier Photogate

Data collection with the Dual-Range Force Sensor and Vernier Photogate is simplified because the LabQuest App automatically calculates the interpolated force. To find the tangential velocity, you must configure the photogate motion timing mode with the circumference information, detailed below.

1. Start the LabQuest App and let it auto-ID the sensors.
2. On the Meter tab of the LabQuest App, tap Mode.
3. Tap User Defined.
4. Enter 1/10 of the circumference of the mass path, or $2\pi r/10$, as the User Defined value. You will need to adjust this value each time you change the radius.
5. On this screen, choose the option to end the data collection with the Stop button.
6. Tap OK.

Collect data and examine the graphs. For further analysis, change one of your graphs to display Force *vs.* Velocity or Force *vs.* Velocity^2.

Logger *Pro* 3 with Wireless Dynamic Sensor System (WDSS)

Start Logger *Pro* software and establish a Bluetooth connection to the device as described in the WDSS manual.

If you want to use a photogate to collect position and tangential velocity data, use one of these Logger *Pro* files.

a. The file CFA-WDSS-Photogate.cmbl, which is part of the file collection on the CFA web page.
b. The Vernier lab manual *Advanced Physics with Vernier – Mechanics* contains an experiment called "12A Centripetal Acceleration" that uses the CFA to investigation circular motion. The book also contains a Logger *Pro* file called "12A Centripetal Acceleration.cmbl" that you can use. The file can be found in the folder called "Supplemental Materials" on the CD that accompanies the book.

Collect data and change the Force-Interpolated *vs.* Time to display Force-Interpolated *vs.* Velocity. Also create and analyze a graph of Force-Interpolated *vs.* Velocity^2.

Collect data and examine the graphs. For further analysis, change one of your graphs to display Force *vs.* Angular Velocity (ω). The file contains a calculated column called Angular Velocity^2 (ω^2). Create and analyze the graph of Force *vs.* Angular Velocity^2 (ω^2).

LabQuest with Wireless Dynamic Sensor System (WDSS)

Start LabQuest App, let it auto-ID the photogate. Establish a Bluetooth connection to the WDSS.

When using a photogate, you will need to set the position increment in photogate motion timing to either 1/10 of the circumference (for tangential velocity) or $2\pi/10$ (for angular velocity).

1. On the Meter tab of the LabQuest App, tap Mode.
2. Tap User Defined.
3. Enter the desired position increment as the User Defined value.
4. On this screen, choose the option to end the data collection with the Stop button.
5. Tap OK.

Collect force data with the WDSS and examine the graphs. For further analysis, change one of your graphs to display Force *vs.* Velocity or Force *vs.* Velocity^2.

Sample Data from the CFA

The following are summaries of experiments that you can perform with the Centripetal Force Apparatus.

Centripetal Force with a Spin

To illustrate the capability of the CFA, here is a quick experiment using a different perspective than is often used. Quite often, centripetal force is investigated using the equation $F=mv^2/r$, where F = centripetal force, m = mass, v = tangential velocity, and r = radius of motion; however, a comparable equation is $F=mr\omega^2$ where ω is the angular velocity of the mass. This suggests an experiment that lets you explore a variety of speeds with one run and with a very simple graphical result. If you simply spin the beam by hand and let it slow down over 30 or 40 seconds, you will have force as a function of angular speed. A graph of force *vs.* the square of the angular speed is a direct proportionality, where the slope represents the product of the mass and radius, since $F=(mr)\omega^2$.

The graph below shows two combinations of mass and radius. In each case, the slope is the product of the mass and radius, and the functional relationship is proportionality. A Vernier Photogate and Dual-Range Force Sensor were used, since those will be most commonly available.
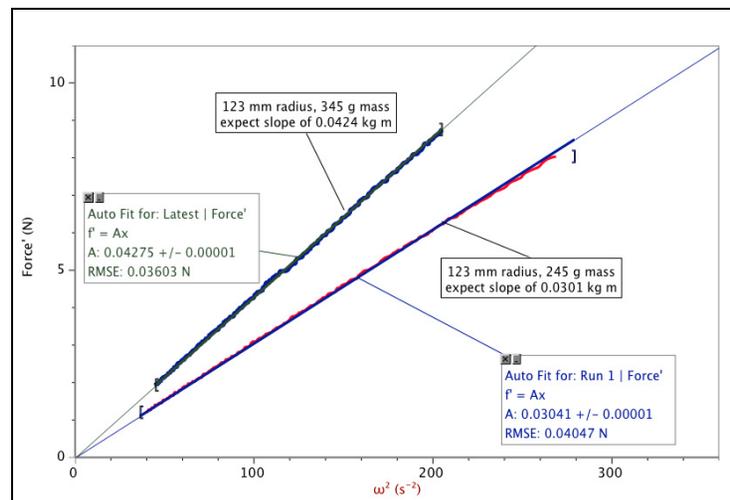
Centripetal Force with a Spin – a Detailed Look

The Vernier lab manual *Advanced Physics with Vernier – Mechanics* has an excellent experiment that investigates $F=mv^2/r$ in a guided inquiry fashion. The experiment is similar to the one mentioned above in that the students spin the Rotating Beam and collect data as it slows down. A graph of F *vs.* v^2 shows a linear relationship. They then vary the mass and determine that the F is directly proportional to m. Next they compare runs with different radii and see that the force is inversely proportional to the radius. The lab called "12A Centripetal Acceleration" is also posted on our web site at www.vernier.com/accessories/cfa/

Moment of Inertia

You can also measure moments of inertia with the CFA. A beginning experiment is to determine the moment of inertia of the entire rotating assembly. This measurement is done by hanging a mass over the Ultra Pulley (which can be attached to the side of the frame) and using a string to attach the mass to the 3-Step Pulley on the Rotating Assembly. Allow the mass to fall, which applies a torque to the system. Use a Vernier Photogate to measure the angular acceleration of the system and then calculate the moment of inertia.

Attach the carriages to the beam and repeat the above experiment to determine the moment inertia of this system and then determine the moment of inertia of the carriages idealized as point masses.

Specifications

Encoder Wheel	10 spokes
Diameters of Pulleys on 3-Step Pulley on Rotational Shaft	20 mm, 29 mm, 48 mm

Other Products for Use with this Kit

Dual-Range Force Sensor (DFS-BTA)

This low-cost force sensor has two ranges: –10 to +10 N and –50 to +50 N. It can be easily mounted on a ring stand or dynamics cart, or used as a replacement for a spring scale. Use it to study friction, simple harmonic motion, impact in collisions, or centripetal force.
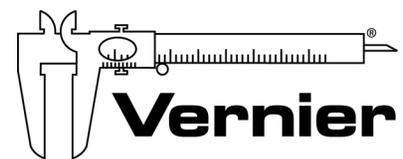
Vernier Photogate (VPG-BTD)

Photogates can be used to study free fall, rolling objects, air track collisions, pendula, etc. This photogate can be easily mounted on a ring stand.

Wireless Dynamic Sensor System (WDSS)

The Wireless Dynamics Sensor System combines a 3-axis accelerometer, altimeter, and force sensor into one unit that communicates wirelessly with your computer using Bluetooth® wireless technology. You can also use it as a standalone data logger.

Warranty

Vernier warrants this product to be free from defects in materials and workmanship for a period of five years from the date of shipment to the customer. This warranty does not cover damage to the product caused by abuse or improper use.