

# Newton's 2nd Law

**Equipment** Capstone, motion sensor, meter stick, force sensor, small bench clamp, rod for force sensor, weights with hooks, 18.7 cm glider, 28.7 cm glider, air track, super pulley with rod, string for gliders, 2 photo gates, photogate stand with thin rod, large picket fence, index cards, and analog scale.

**Photogate:** A digital sensor shaped like a U. An infrared (880 nm) beam is passed between the legs of the U. When an object passes in front of the beam, a light on the sensor turns on and the output goes from high to low. Usually, Capstone's 20 Hz clock starts timing when the beam is blocked and stops when unblocked. This sequence can be repeated if the beam continues to be blocked and unblocked.

**Force Sensor:** An analogue sensor that measures force in newtons (N) by means of a strain guage. This sensor has a hook which records a positive force when it is pushed and a negative force when pulled. The maximum force is  $\pm 50$  N. (1 N=0.2248 lb.) The force sensor can be calibrated by clicking the calibration icon on Capstone and following the steps provided. There is a tare button on the sensor which zeros it even if there is a force on it. This is a very useful feature that allows you to set a given force as zero and have the sensor record only the change in force.

**Smart Pulley:** A digital sensor that combines a photogate sensor with a spoked pulley. As the pulley turns, its spokes block the photogate beam. If a string is passed over the smart pulley a display can be programmed to give position, velocity, acceleration, *etc.*

**Picket Fence:** A clear plastic sheet with opaque bands. When it is passed through a photogate, the beam is alternately blocked and transmitted. A display can be programmed to give the position, velocity, acceleration, *etc.*, of the picket fence. It is necessary to program the display for the band distance.

## 1 Purpose

To explore Newton's 2nd law and some of its applications.

## 2 Theory

Let  $\mathbf{F}$  be the force in newtons (N),  $m$  the mass in kilograms (kg), and  $\mathbf{a}$  the acceleration in  $\text{m/s}^2$ . Newton's 2nd law states that

$$\mathbf{F} = m\mathbf{a} . \tag{1}$$

This is a vector equation, but in this lab the motions are in one linear dimension so the vector notation can be dropped. This law can be applied to an entire system or any part of the system. Here, we assume that the system is a rigid body with forces applied in such a way that the body does not rotate. The force  $\mathbf{F}$  is the sum of all the forces acting on the chosen body or system; it can also be called the net force or the total force.

Let  $m$  be the mass of an object on or near the surface of the earth,  $M$  the mass of the earth,  $R$  the radius of the earth, and  $G$  Newton's gravitational constant. The gravitational force  $F_G$  between  $m$  and  $M$  is given by Newton's gravitational law as

$$F_G = \frac{GMm}{R^2} = mg, \quad (2)$$

where  $g$  is the acceleration due to gravity (on the surface of the earth) and is given by

$$g = \frac{GM}{R^2} = 9.81 \text{ m/s}^2. \quad (3)$$

$F_G$ , more popularly known as weight, has two important applications.

1. The weight of an object in N is equal to its mass in kg times  $g = 9.81 \text{ m/s}^2$ .
2. If the only force on a dropped object is  $F_G$ , then Newton's 2nd law gives  $mg = ma$ , or  $a = g$ . Hence the name for  $g$ .

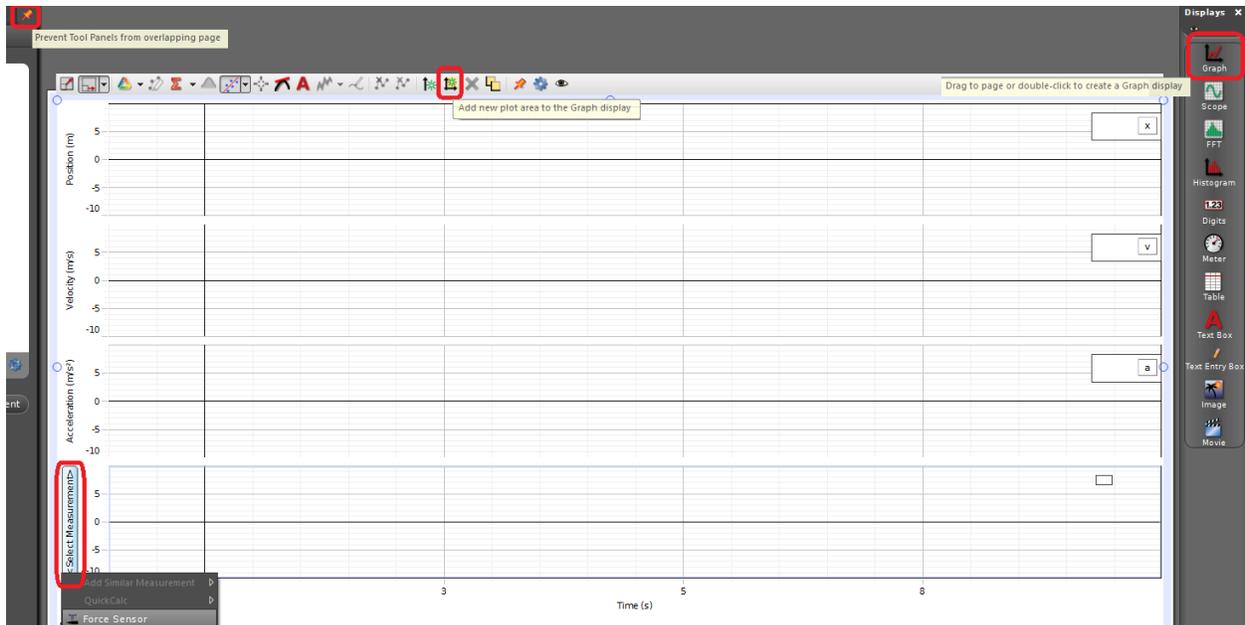
### 3 Does $F = ma$ ?

#### 3.1 Description

The force sensor will be used to measure the net force  $F$  on a mass  $m$ . The motion sensor will be used to measure the acceleration  $a$ , which should be equal to  $F/m$  if Newton's 2nd law holds.

#### 3.2 Programming

Plug in the motion and force sensors, note the channels you use, and program Capstone for them. You may use the default speed of sound and sample rate for the motion sensor. Click and drag the **Graph** icon from the **Displays** window to the center screen. Create 4 graphs and label them position, velocity, acceleration, and force. You will use **Add new plot area to the Graph display** icon for additional graphs. Look at the following illustration for guidance.



### 3.3 Calibrating the Force Sensor

You need to run the program to calibrate the Force Sensor. Click the **Record** button in Capstone. Suspend the force sensor from a horizontal rod. Hang a 0.5 kg mass on the hook of the sensor and press the tare button to zero the sensor. The idea is to null out the force on the 0.5 kg mass due to gravity so that the force sensor only measures the additional force on the mass due to its acceleration. Click **Calibration** in the **Tools** window and do the following.

- Select force as the measurement you want to calibrate, then click Next.
- Choose “Two Standards (2 point),” then click Next. You have just set it to calibrate the sensor for 2 different points.
- For the first point, change the **Standard Value** to 0 N and click “Set current value to standard value.”
- Before calibrating the second point, hang two 0.2 kg masses from the 0.5 kg mass.
- Enter the combined weight of the 0.2 kg masses ( $0.400 \times 9.81 = 3.92$  N) into the second **Standard Value** box and click “Set current value to standard value.”
- Click Finish.
- Click **Stop** in the Capstone program.
- Remove the two 0.2 kg masses from the force sensor but leave the 0.5 kg mass.
- Go to the **Data Summary** in the Tools column and delete the data it recorded.

The force sensor has been calibrated to read zero when the 0.5 kg mass is at rest, so the output of the force sensor now reads the force only when the mass is accelerated.

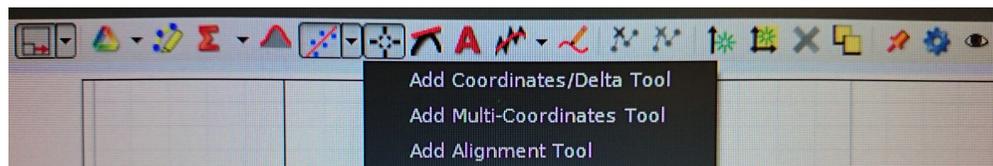
### 3.4 Data Acquisition

Place the motion sensor on the floor with the grill pointing up. Be sure that it is far enough away from the edge of the bench so that it does not measure the height of the bench. Carefully hold the force sensor with the 0.5 kg mass attached over the motion sensor. Have your partner click Record and move the force sensor up and down 3 times in a vertical line above the motion sensor. Click Stop. Examine your data. You should take several runs to determine how to get the best data. You will probably do better if you move the sensor fairly quickly up and down, but not so quickly that the mass disengages from the sensor.

Take care to make sure that the motion sensor is measuring the movement of the mass up and down. You may wish to tape an index card to the bottom of the mass to give the motion sensor a better target. Be sure to note this and any other steps you take to optimize the measurement of the motion of the mass.

### 3.5 Analysis

Compare the graph for force with the graph for acceleration. Use **Add Multi-Coordinate Tool** to better analyze the graphs.



Does the curve for force pretty much duplicate the shape of the curve for acceleration? Are the magnitudes what they should be? What about the zero crossings? If you made exactly the same motion with the force sensor but at a different distance from the motion sensor, which of your 4 graphs would differ from the ones you actually took?

## 4 Newton's 2nd Law Applied to a System.

### 4.1 Description

Newton's 2nd law is tested with a system of 2 masses connected by a string. Mass  $M_1$  is hanging from a vertical string that goes over a smart pulley and is attached horizontally to a glider  $M_2$  that lies on a horizontal air track. The glider is held stationary on the air track and then let go. The motion of the string and hence of the glider is measured by the smart pulley.

## 4.2 Theory

Let the tension in the string be  $T$  and the common acceleration of the masses be  $a$ . If the positive directions are taken as down for  $M_1$  and toward the pulley for  $M_2$ , then the 2nd law applied to each gives

$$M_1g - T = M_1a \quad (4)$$

$$T = M_2a . \quad (5)$$

Eliminating  $T$  gives

$$a = \frac{M_1}{M_1 + M_2}g . \quad (6)$$

The above analysis assumes that the pulley is massless and frictionless to the extent that the mass and friction of the pulley cannot be neglected. The tension in the string is different on each side of the pulley.

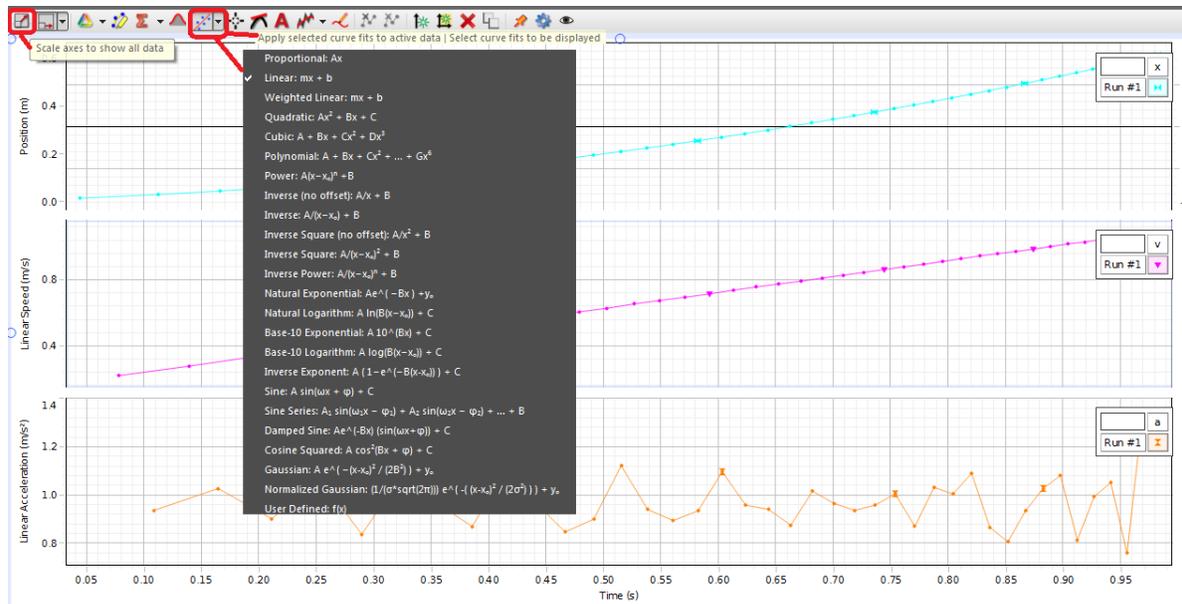
## 4.3 Set-up and Programming

Restart Capstone. Assemble the photogate with super pulley on rod. Position the small bench clamp at the end of the air track with the screw on top, and insert the photogate with super pulley on rod. Plug in the photogate with pulley and note the channel. Program Capstone for **Photogate with Pulley**. Click **Timer Setup** under **Tools** and make sure position, linear speed, and linear acceleration are all checked. Set up graphs for position, linear speed, and linear acceleration.

First use the 18.7 cm glider and level the air track. Attach one loop of string to the glider, pass the string over the pulley, and attach the other loop to a 10 g mass. Adjust the smart pulley so that the string horizontal over the air track and passes through the groove at the end of the track. Move the glider a few inches from the pulley, and check that the mass hits the floor.

## 4.4 Data acquisition

Turn the airtrack on. Draw the glider back from the end of the track as far as you can without having the mass hit the clamp holding the photogate with pulley. Let go of the glider and click **Record** at the same time. Click **Stop** just before the glider hits the end of the air track. Click on Linear speed graph. Next, click on the **Scale axes to show all data** icon. Click on **Apply selected curve fits to active data** icon and select Linear. Determine the slope of the linear speed curve. To rescale an individual graph click on the graph and then **Scale axes to show all data** icon. Also, if needed click the **Highlight range of points in active data** button to select good parts of the graph. The highlight range is located next to the sigma icon.



Determine the acceleration  $a$ . Repeat for masses of 20 g and 30 g, and then the 28.7 cm long glider with masses of 30, 40, and 50 grams.

## 4.5 Analysis

Compare your results to the theoretical values. How well do they agree? What are possible reasons for any disagreement? Try to make sense of the magnitude of any discrepancies.

## 5 The acceleration of gravity $g$

### 5.1 Description

A picket fence is dropped through a digital photogate sensor. The acceleration of the picket fence is measured and compared to  $g$ .

### 5.2 Set-up and Programming

Restart Capstone. Assemble the photogate with thin rod and stand. Place the photogate assembly stand near the edge of the bench and have the photogate itself extend over the edge of the bench. Plug in photogate sensor and note the channel. Program Capstone for the digital sensor and choose **Picket Fence**. Click on **Timer Setup** and note the Flag Length is 0.05 m. Verify this by measuring the distance from the top of one opaque band to the top of the next using the meter stick. Create graphs for speed and acceleration.

### 5.3 Taking data

Put a few coats on the floor directly beneath the photogate to act as a cushion for when the picket fence hits the floor. Hold the picket just above the photogate, click the Record button, and let go of the picket fence. Click Stop. (Capstone does not actually take data until the photogate beam is first blocked, so there is no need to drop the picket fence immediately

after the Start button is clicked.) Determine the acceleration of the picket fence. Take a few runs to have some statistics.

Always click upon the graph you want to analyze. To take the mean average value of the acceleration curve click on the acceleration graph. Click on the down arrow next to sigma icon and check Mean. Click on the sigma button and the overall mean average value will come up. Select the best part of the graph with the highlight feature.



## 5.4 Analysis

Compare your results to the accepted value of  $g$ . What contributes to errors? If you were able to release the picket a considerable distance above the photogate and still have it go through the photogate (please do not do this as you might damage the picket fence and/or the photo gate), would your results be as accurate? Explain.

## 6 Finishing

Please disassemble the various components and return the bench to the condition in which you found it. Thank you.