Newton's Second Law

INTRODUCTION

In your discussion of Newton's first law, you learned that when the sum of the forces acting on an object is zero, its velocity does not change. However, when a net force acts on the object, it accelerates. In this experiment, you will determine the relationship between the net force acting on an object and its acceleration.

OBJECTIVES

In this experiment, you will

- Identify the forces acting on an object both when its change in velocity, Δv, is zero and when it is accelerating.
- Collect force, velocity, and time data as a cart is accelerated on a track.
- Use graphical methods to determine the acceleration of the cart.
- Determine the relationship between the cart's acceleration and the net force applied to it.
- Determine the effect of the mass on the relationship between acceleration and force.

MATERIALS

Vernier data-collection interface	standard hooked or slotted lab masses
Logger *Pro* or LabQuest App	Vernier Dynamics Track
Dual-Range Force Sensor **or**	standard cart
Wireless Dynamic Sensor System	Ultra Pulley and Pulley Bracket
Vernier Photogate and Bracket and	lightweight mass hanger
Cart Picket Fence, **or**	
Motion Detector	

PRE-LAB INVESTIGATION

Your instructor will show you the apparatus for this experiment. It is called a "modified Atwood's machine." A weight is connected to a cart by a string over a pulley. When the weight is allowed to fall, observe the motion of the cart. A force sensor mounted on the cart enables you to measure the force acting on the cart when it is moving. Discuss how you could determine the acceleration of the cart. Then, consider how the acceleration varies as the force applied to the cart increases. On the axes to the right, draw a sketch of the acceleration *vs.* net force graph based on your observations.
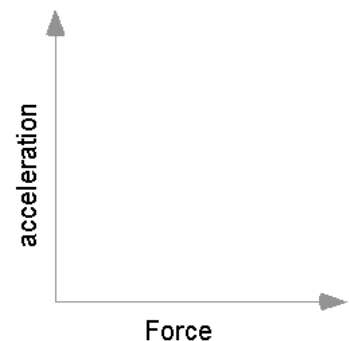
PROCEDURE

There are three methods one can use to collect velocity *vs.* time data and determine the acceleration of the cart. Choose the method that matches the apparatus you are using.

Method 1 Timing with a Photogate and Picket Fence

1. Attach an Ultra Pulley to the Pulley Bracket; attach this assembly to one end of the Dynamics Track. Make sure that you have adjusted the track to make frictional forces negligible.

2. Connect the Dual-Range Force Sensor (DFS) and a Photogate to the interface; then start the data-collection program. You will need only graphs of force *vs.* time and velocity *vs.* time, so you can delete others and then re-size graphs to make them easier to see. LabQuest App users can do this in the Graph Options menu.

3. Place the Cart Picket Fence in the slot on the cart so that the alternating dark and clear bands are on the top. Now place the force sensor on the cart.

4. Position the photogate (using a support rod and clamp) so that the alternating dark and clear bands on the picket fence will interrupt the beam, as shown in Figure 1.
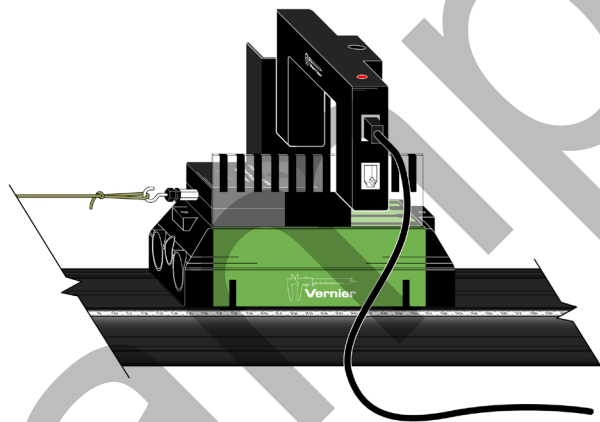

Figure 1

5. Discuss with your instructor what range of masses to use to apply the force that will accelerate the cart. Determine the total mass of your cart, force sensor, and any additional mass you may be instructed to use.

6. Set up data collection.

    Using Logger *Pro*

    a. Choose Set Up Sensors ► Show All Interfaces from the Experiment menu.
    b. Click the image of the Photogate, select Set Distance or Length, then select Cart Picket Fence from the list of devices.
    c. Choose Data Collection from the Experiment menu. In the Mode list, click Digital Events. End collection after 20 Events.

    Using LabQuest as a standalone device

    • Data collection defaults to Photogate Timing mode. Tap Mode, select User defined, and set the length to 0.01 m.

7. Disconnect the hanging mass from the force sensor, then zero the sensor.

8. Re-connect the hanging mass to the Force Sensor. Position the Photogate so that the cart and picket fence pass through the photogate while the cart is accelerating (before the hanging mass stops moving). Use something to cushion the hanging weight when it strikes the floor.

9. Start data collection, then release the cart.

10. To determine the force acting on the cart, select the portion of the force *vs.* time graph corresponding to the interval during which the cart's velocity was changing smoothly. Find the statistics for this interval. Manual scaling of your graph is more helpful for doing this than Autoscaling.

11. To determine the acceleration of the cart, perform a linear fit on the velocity *vs.* time graph. Be sure to record the values of force and acceleration for this hanging mass in your lab notebook.

12. Repeat Steps 9–11 until you have three pairs of force *vs.* acceleration data that are reasonably consistent for that mass.

13. Increase the hanging mass and continue until you have acceleration *vs.* force data for at least five different hanging masses.

Method 2 Timing with a Photogate and Ultra Pulley

1. Attach an Ultra Pulley to the Pulley Bracket; attach this assembly to one end of the Dynamics Track. Make sure that you have adjusted the track to make frictional forces negligible.

2. Connect the Dual-Range Force Sensor (DFS) and a Photogate to the interface; then start the data-collection program. You will need only graphs of force *vs.* time and velocity *vs.* time, so you can delete others and then re-size graphs to make them easier to see. LabQuest App users can do this in the Graph Options menu.

3. Attach the force sensor to the cart.

4. Attach the photogate to the track using a bracket so that the spokes on the pulley interrupt the beam, as shown in Figure 2.
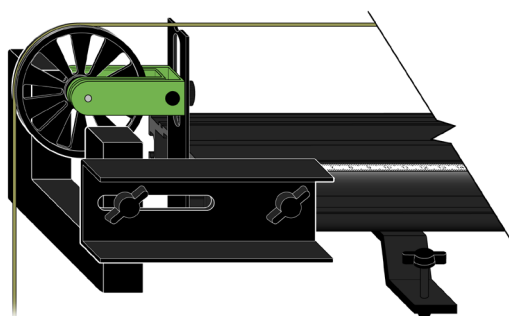

Figure 2

5. Discuss with your instructor what range of masses to use to apply the force that will accelerate the cart. Determine the total mass of your cart, force sensor, and any additional mass you may be instructed to use.

6. Set up data collection.

   Using Logger *Pro*

   a. Choose Set Up Sensors ► Show All Interfaces from the Experiment menu.
   b. Click the image of the Photogate, select Set Distance or Length, then select Ultra Pulley (10 Spoke) Inside from the list of devices.

   Using LabQuest as a standalone device

   - Data collection defaults to Photogate Timing mode. Tap Mode and select Pulley (10 spoke) ► inside edge.

7. Disconnect the hanging mass from the force sensor, then zero the sensor.

8. Re-connect the hanging mass to the force sensor. Position the cart so that the hanger has about 30 cm to fall. Use something to cushion the hanging weight when it strikes the floor.

9. Begin collecting data, then release the cart. Stop data collection after the weight hits the cushion on the floor.

10. To determine the force acting on the cart, select the portion of the force *vs.* time graph corresponding to the interval during which the cart's velocity was changing smoothly. Find the statistics for this interval. Manual scaling of your graph is more helpful for doing this than Autoscaling.

11. To determine the acceleration of the cart, perform a linear fit on the portion of the velocity-time graph during which the velocity is changing smoothly. Be sure to record the values of force and acceleration for this hanging mass in your lab notebook.

12. Repeat Steps 9–11 until you have three pairs of force *vs.* acceleration data that are reasonably consistent for that mass.

13. Increase the hanging mass and continue until you have acceleration-force data for at least five different hanging masses.

Method 3 Timing with a Motion Detector

1. Attach an Ultra Pulley to the Pulley Bracket; attach this assembly to one end of the Dynamics Track. Make sure that you have adjusted the track to make frictional forces negligible.

2. Connect the Dual-Range Force Sensor (DFS) and a Motion Detector to the interface; then start the data-collection program. You will need only graphs of force *vs.* time and velocity *vs.* time, so you can delete others and then re-size graphs to make them easier to see. LabQuest App users can do this in the Graph Options menu.

3. Attach the force sensor to the cart. Mount the motion detector at the end of the track opposite the pulley. If your motion detector has a switch, set it to Track.

4. Discuss with your instructor what range of masses to use to apply the force that will accelerate the cart. Determine the total mass of your cart, force sensor, and any additional mass you may be instructed to use.

5. Set up data collection.

    Using Logger *Pro*

    a. Choose Data Collection from the Experiment menu.
    b. Reduce the length of time to 3 seconds.

    Using LabQuest as a standalone device

    a. Tap Length and change the length of data collection to 3 seconds.
    b. Change the time to 3 seconds on the x-axis column using Graph Options in the graph tab.

6. Position the cart so that the hanging mass is approximately 30 cm from the floor, disconnect the hanging mass from the force sensor, then zero both sensors. Make sure the starting position of the cart is at least 20 cm from the motion detector.[1]

7. Re-connect the hanging mass, begin collecting data, then release the cart. Catch the hanging mass before it strikes the floor.

8. To determine the force acting on the cart, select the portion of the force *vs.* time graph corresponding to the interval during which the cart's velocity was changing smoothly. Find the statistics for this interval. Manual scaling of your graph is more helpful for doing this than Autoscaling.

9. To determine the acceleration of the cart, perform a linear fit on the portion of the velocity *vs.* time graph during which the velocity is changing smoothly.

    Be sure to record the values of force and acceleration for this hanging mass in your lab notebook.

10. Repeat Steps 7–9 until you have three pairs of force *vs.* acceleration data that are reasonably consistent for that mass.

11. Increase the hanging mass and continue until you have acceleration *vs.* force data for at least five different hanging masses.

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[1] If you are using an older Motion Detector without a position switch, the cart needs to be at least 45 cm from the detector.

EVALUATION OF DATA

1. To evaluate the relationship between acceleration and force, disconnect the sensors and choose New from the File menu.

2. Even though you investigated how acceleration responded to changes in the force, in order to facilitate your analysis of data, plot a graph of force *vs.* acceleration.

3. If the relationship between force and acceleration appears to be linear, fit a straight line to your data. If possible, print a copy of your data table and graph.

4. Write the equation that represents the relationship between the force, F, acting on the cart and the cart's acceleration, a. Be sure to record the value of the mass of the cart, sensor and any additional masses you used.

5. Write a statement that describes the relationship between the force acting on the cart and the cart's acceleration.

6. Compare your results to those obtained by others in class. What relationship appears to exist between the slope of the graph of *F vs. a* and the mass that was accelerated?

7. Assuming that the conclusion you reached in Step 6 is correct, express the SI unit of force, N, in terms of the fundamental units of mass, length and time.

8. Write a general equation that expresses the relationship between the force, mass and acceleration.

EXTENSION

Examine the force *vs.* time graph for one of your trials. Explain why the force reading decreases as the cart is released and accelerates.

Suppose that you had kept the net force acting on the cart the same, but varied the mass instead. Predict the shape of the graph of acceleration *vs.* mass. Your answer to the question above should suggest why it would be very difficult to perform an experiment to test your prediction. Explain.

INSTRUCTOR INFORMATION

Newton's Second Law

This is the second in a series of three experiments designed to help students develop an understanding of Newton's laws of motion. It is written with the assumption that the instructor will engage the students in discussions at critical junctures. These discussions can take place with the entire class or with individual lab groups. The icon at left indicates where these discussions should occur.

The Microsoft Word files for the student pages can be found on the CD that accompanies this book. See *Appendix A* for more information.

OBJECTIVES

In this experiment, the student objectives include

- Identify the forces acting on an object both when its change in velocity, Δv, is zero and when it is accelerating.
- Collect force, velocity and time data as a cart is accelerated on a track.
- Use graphical methods to determine the acceleration of the cart.
- Determine the relationship between the cart's acceleration and the net force applied to it.
- Determine the effect of the mass on the relationship between acceleration and net force.

During this experiment, you will help the students

- Recognize that the acceleration of an object is the slope of a velocity *vs.* time graph.
- Recognize that the slope of a graph of two variables in a physical system is usually a function of variables(s) that are held constant.
- Derive an equation for Newton's second law: $F_{net} = ma$ or $\sum F = ma$.

REQUIRED SKILLS

In order for student success in this experiment, it is expected that students know how to

- Zero a Motion Detector. This is addressed in Activity 2.
- Perform linear and curve fits to graphs. This is addressed in Activity 1.
- Zero a Force Sensor.

EQUIPMENT TIPS

There are a number of ways one could collect suitable data for the analysis called for in this experiment. Three variations are described in the student version of the experiment. A fourth, using the Wireless Dynamic Sensor System (WDSS) is described in this document. Depending on the equipment available to students, you may wish to allow them to use different approaches to collect the data.

The first method suggested for obtaining velocity-time data–using a photogate and cart picket fence–is intended to build on student experience with the larger picket fence in Experiment 2. Students should recognize that, as the cart accelerates through the photogate, the time from blocked state to blocked state decreases. It follows that the fixed distance (1.0 cm) divided by smaller intervals of time yields increasing values of velocity (see Figure 1).
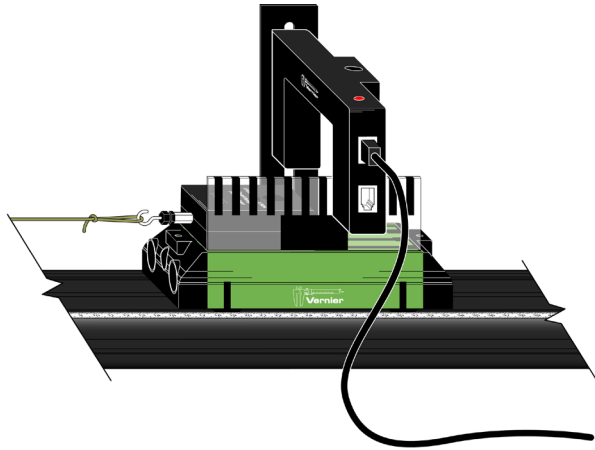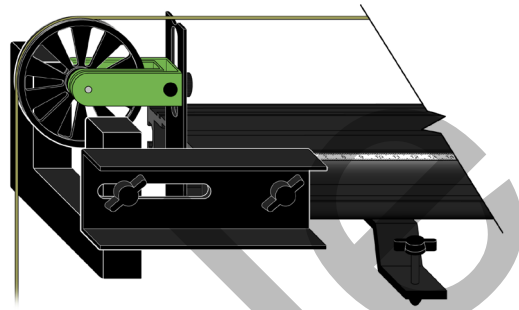

Figure 1

Figure 2

In the second method, the photogate is attached to the end of the track with a bracket. However, it may require some discussion to convince students that the spokes on the ultra pulley serve the same purpose as the dark bands on the picket fence (see Figure 2).

The third method, use of a Motion Detector, follows naturally from Experiment 3 and yields good data as well. Make sure that the Motion Detector is set to Track mode. If you do not have enough Dynamics Tracks for all the groups, this experiment can be performed on a lab table top. You will have to attach the pulley to the edge of the table.

The Wireless Dynamic Sensor System has the advantage over the DFS of not worrying about wire to the Force Sensor impeding the motion of the cart. While it provides acceleration as well as force data, we suggest using the other timing methods because the acceleration *vs.* time data for this experiment are sufficiently noisy that students would find it difficult to interpret the data.

Slotted or drilled lab masses can be suspended from the string using a lightweight hanger, or even a large paper clip. Use of a lightweight mass hanger allows the opportunity to examine accelerations for a wider range of values of force. The sample data were obtained using hanging masses ranging from 25–125 g.

The mass of the standard cart and DFS is approximately 630 g. If you instruct different lab groups to place additional masses on the cart (100 g increments work well), they can investigate the effect of mass on their force *vs.* acceleration graph when they compare their results.

PRE-LAB DISCUSSION

This experiment should be performed only after a thorough discussion of Newton's first law. Students should recognize that if the sum of the forces acting on an object is not zero, the object accelerates. The purpose of this experiment is to determine the relationship between the net force acting on an object and its acceleration.

Demonstrate to the students the modified Atwood's apparatus. Remind the students that the Force Sensor measures only the force applied by the hanging weights. In order to accurately determine the relationship between force and acceleration, it is important to reduce the effect of frictional forces (which are not easily measured) on the cart. To achieve this, the end of the track opposite the pulley is elevated slightly to introduce a small component of the force of gravity. When these two forces cancel, the cart should move with nearly constant velocity when given a gentle shove.

Once this condition has been met, connect the hanging weight to the cart, release the cart and allow it to accelerate toward the pulley. Make sure that the string is long enough so that the weights reach the floor before the cart reaches the pulley. Ask the students if they could observe a change in the motion of the cart once a net force no longer acted on the cart. You may have to use a low towing weight for students to notice. Now, ask students to predict the shape of the graph of acceleration *vs.* force. Once they have done this, they can begin the experiment.

LAB PERFORMANCE NOTES

Whichever way students collect data, they should record force and acceleration data for multiple trials for each hanging mass in their lab notebooks. When they feel that they have three reasonably consistent values of force and acceleration, they can increment the hanging mass. They should obtain force and acceleration data for at least five different hanging masses.

Computer Data Collection

Students should connect the Dual-Range Force Sensor (DFS)[1] to an analog port and a Photogate (or Motion Detector) to a digital port on the interface; then start the Logger *Pro*. They will need only graphs of force *vs.* time and velocity *vs.* time, so they should delete others and then re-size graphs to make them easier to see. More explicit instructions than usual are provided in the student pages because there are multiple timing options. If students are using a version of Logger *Pro* prior to version 3.8.3, they will need to use the following steps to set up the Cart Picket Fence or Ultra Pulley.

- Choose Set Up Sensors▶Show All Interfaces from the Experiment menu.
- Click the image of the photogate, select Set Distance or Length, then set the appropriate conditions (User Defined▶0.01 m with the cart picket fence, or Ultra Pulley (10 Spoke) Inside Edge).
- If you are using the cart picket fence, choose Data Collection from the Experiment menu. In the Mode list, click Digital Events. End collection after 20 Events.

LabQuest App Data Collection

Students should connect the Dual-Range Force Sensor (DFS) to an analog port and a Photogate (or Motion Detector) to a digital port on the interface. Force and Gate State (or Position) fields

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[1] A Wireless Dynamic Sensor System can be used in place of the DFS.

appear in the Sensor window. They will need only graphs of force *vs.* time and velocity *vs.* time, so they should select Graph Options in the Graph tab and choose velocity for the Graph 2 *y*-axis. Explicit instructions are provided in the student pages for each of these timing options.

With either method of data collection, after each trial, students need to find statistics for the portion of the force *vs.* time graph during which the cart was accelerating; they should record the mean force for this interval. They should perform a linear fit on the portion of the velocity-time graph during which the velocity was changing smoothly, and record the slope as the acceleration. An example is shown in Figure 3.

This analysis is more easily done in Logger *Pro*, but can be accomplished without great difficulty in LabQuest App.

Note: Students might wonder why the force reading decreases as the cart is released and accelerates. Suggest that they will address this phenomenon in the post-lab extension.
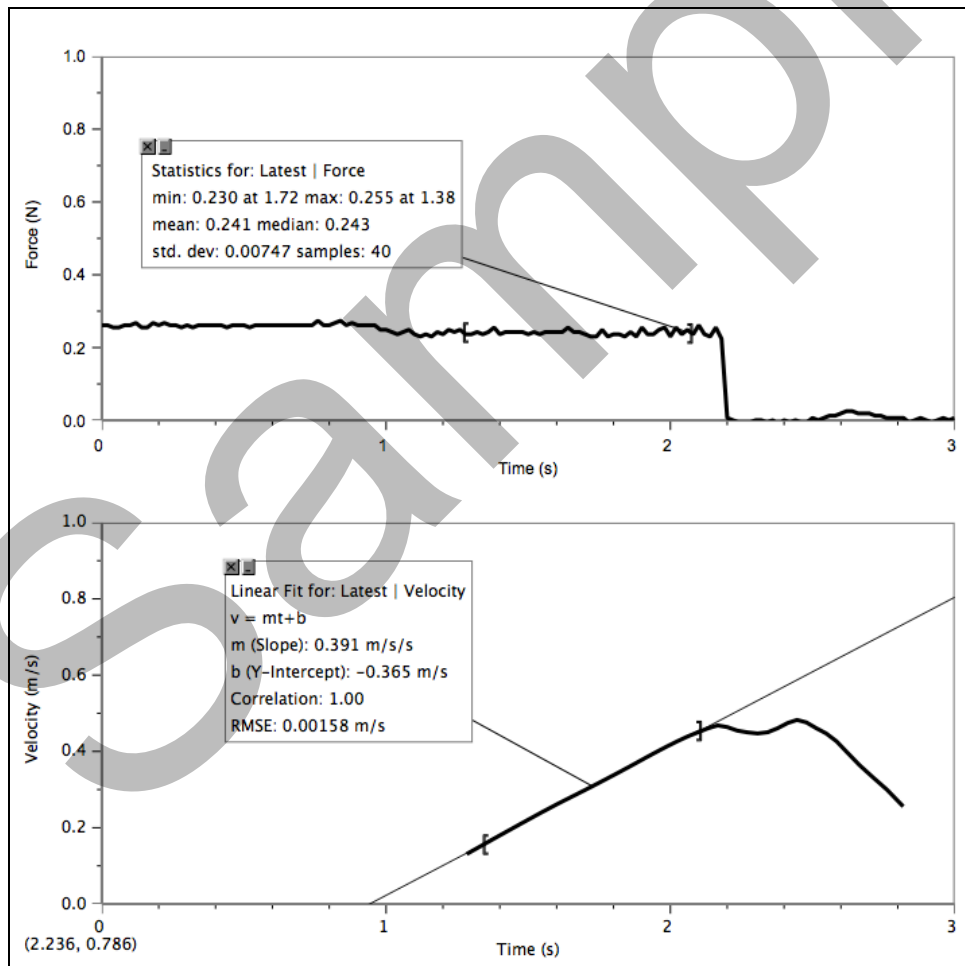
SAMPLE RESULTS AND POST-LAB DISCUSSION

Figure 3 Timing with the photogate and ultra pulley

Steps 1–3

Suggest to the students that while we ordinarily place the independent variable on the *x*-axis, sometimes, to facilitate the analysis of the graph, we choose to ignore that convention. The graph in Figure 4 shows the plot of force *vs.* acceleration using the photogate with the cart picket fence and Logger *Pro* to collect data. Similar results were obtained with the other methods of data collection.
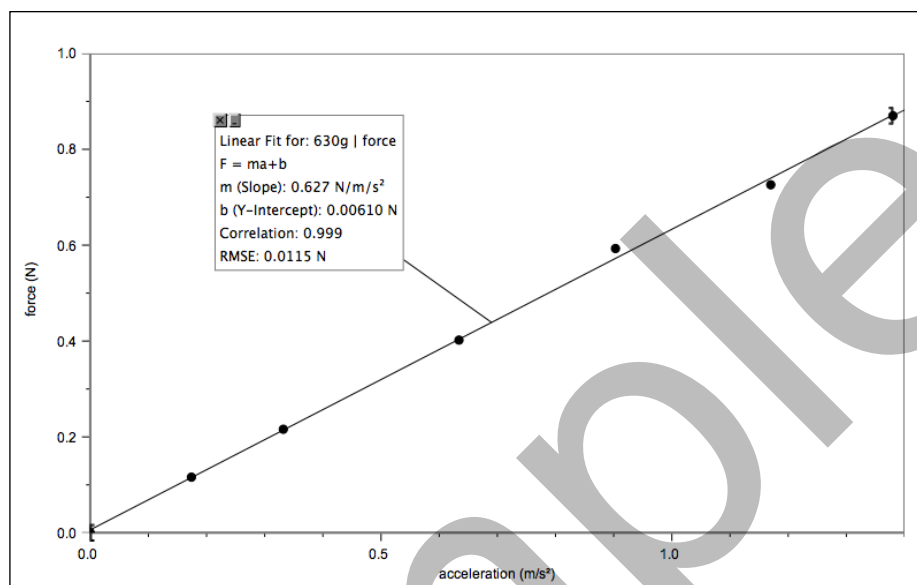

Linear Fit for: 630g | force
F = ma+b
m (Slope): 0.627 N/m/s²
b (Y-Intercept): 0.00610 N
Correlation: 0.999
RMSE: 0.0115 N

Figure 4

Steps 4–5

For the graph above, the equation describing the relationship between force and mass is

$$F_{net} = (0.627 \frac{N}{m/s^2})a$$

Students should be able to state that the force is directly proportional to the acceleration of the cart and masses.

Step 6

Note that the slope of the graph (0.627 N/(m/s²)) is within 1% of the mass of the cart and the sensor. With increasing mass, the agreement is slightly worse, but still within 3%. This is an appropriate time to suggest that the slope of a graph of variables in a physical system is usually related, in some way, to a variable that was held constant during the experiment. In this case, students held mass constant.

Step 7

If the value of the slope of the graph is equivalent to the mass of the object undergoing acceleration, then the units of the slope must simplify to kilograms. This suggests that the fundamental units of the newton are $\frac{kg}{m/s^2}$. Encourage students to make this substitution for N in the numerator and cancel out m/s², leaving kg, the unit for mass.

Step 8

The analysis in Step 7 leads to the conclusion that the general equation that describes the relationship between net force and acceleration is $F_{net} = ma$.

EXTENSION

Students might wonder why the force decreases slightly when the cart is released (see Figure 3). To answer this question, they should sketch free-body diagrams for the hanging mass and the cart when they are both motionless. The tension force in the string has the same magnitude as the weight of the hanging mass. This same force acts on the cart. When the cart is released, the tension force must be smaller than the weight of the hanging mass; otherwise, the hanging mass (and cart) would not accelerate.

Some portion of the force of gravity acting on the hanging mass accelerates this mass as well as cart/sensor/mass system. As the hanging mass increases, the difference between the force of tension in the static and accelerating conditions increases because the hanging mass represents an increasing fraction of the overall mass of the *system* that is accelerating.

If you were to keep the hanging mass constant, but vary the mass of the cart, the force of tension in the static condition would remain the same. However, when the cart was released, the tension acting on the cart would decrease slightly for each increase in mass.