Investigate Physics Using Sensors

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HANDS-ON ACTIVITIES

Static and Kinetic Friction

- Go Direct Force and Acceleration

The Magnetic Field of a Permanent Magnet

- Go Direct 3-Axis Magnetic Field

Cart on a Ramp

- Go Direct Sensor Cart

Impulse and Momentum

- Go Direct Sensor Cart

Static and Kinetic Friction

(Force and Acceleration Sensor)

If you try to slide a heavy box resting on the floor, you may find it difficult to get the box moving. *Static friction* is the force that counters your force on the box. If you apply a light horizontal push that does not move the box, the static friction force is also small and directly opposite to your push. If you push harder, the friction force increases to match the magnitude of your push. There is a limit to the magnitude of static friction, so eventually you may be able to apply a force larger than the maximum static force, and the box will move. The maximum static friction force is sometimes referred to as *starting friction*. We model static friction, F_{static}, with the inequality $F_{static} \leq \mu_s N$ where μ_s is the coefficient of static friction and N is the *normal* force exerted by a surface on the object. The normal force is defined as the perpendicular component of the force exerted by the surface. In this case, the normal force is equal to the weight of the object.

Once the box starts to slide, you must continue to exert a force to keep the object moving, or friction will slow it to a stop. The friction acting on the box while it is moving is called *kinetic friction*. In order to slide the box with a constant velocity, a force equivalent to the force of kinetic friction must be applied. Kinetic friction is sometimes referred to as *sliding friction*. Both static and kinetic friction depend on the surfaces of the box and the floor, and on how hard the box and floor are pressed together. We model kinetic friction with $F_{kinetic} = \mu_k N$, where μ_k is the coefficient of kinetic friction.

In this experiment, you will use a force sensor to study static friction and kinetic friction on a wooden block. A motion detector will also be used to analyze the kinetic friction acting on a sliding block.

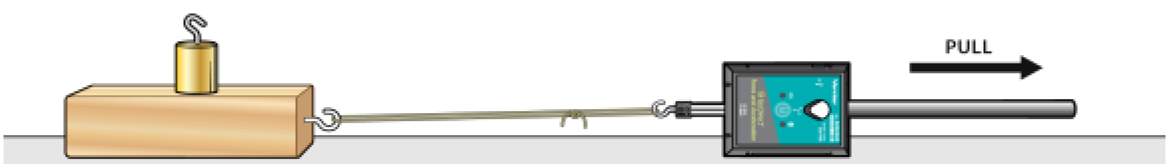

Figure 1

OBJECTIVES

- Use a force sensor to measure the force of static and kinetic friction.
- Determine the relationship between force of static friction and the weight of an object.
- Measure the coefficients of static and kinetic friction for a particular block and track.
- Use a motion detector to independently measure the coefficient of kinetic friction and compare it to the previously measured value.
- Determine if the coefficient of kinetic friction depends on weight.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Motion
Go Direct Force and Acceleration
string
block of wood with hook
balance **or** scale
mass set

PRELIMINARY QUESTIONS

1. In everyday life, you often experience one object sliding against another. Sometimes they slip easily and other times they do not. List some things that seem to affect how easily objects slide.

2. Consider a box sitting on a table. It takes a large force to move it at constant speed. List at least two ways you could reduce the force needed to move the box at constant speed.

3. In pushing a heavy box across the floor, is the force you need to apply to start the box moving greater than, less than, or the same as the force needed to keep the box moving? On what are you basing your answer?

PROCEDURE

Part I Starting Friction

1. Measure the mass of the block and record it in the data table.

2. Launch Graphical Analysis. Connect the Go Direct Force and Acceleration Sensor to your Chromebook, computer, or mobile device.

3. Tie one end of a string to the hook on the force sensor and the other end to the hook on the wooden block. Place a total of 1 kg mass on top of the block, fastened so the masses cannot shift. Before you collect data, practice pulling the block and masses with the force sensor using a straight-line motion. Slowly and gently pull horizontally with a small force. *Very gradually*, taking one full second, increase the force until the block starts to slide, and then keep the block moving at a constant speed for another second.

4. Sketch a graph of force *vs.* time for the force you felt on your hand. Label the portion of the graph corresponding to the block at rest, the time when the block just started to move, and the time when the block was moving at constant speed.

5. Zero the force sensor before collecting data.

   a. Place the force sensor on a flat surface so the working axis is horizontal.

   b. With the force sensor axis held horizontally and no force applied, click or tap the Force meter and choose Zero.

6. Hold the force sensor in position, ready to pull the block, but with no tension in the string.
7. Click or tap Collect to start data collection. Wait a moment, then pull the block as before, taking care to increase the force gradually.
8. Inspect your graph. It should reflect the desired motion, including pulling the block at constant speed once it begins moving. If it does not, start data collection and repeat the pulling process. Print or sketch the graph for later reference.

Part II Peak Static Friction and Kinetic Friction

In this part, you will measure the peak static friction force and the kinetic friction force as a function of the normal force on the block, as shown in Figure 1. In each run, you will pull the block as before, but by changing the masses on the block, you will vary the normal force on the block.

9. Remove all masses from the block.
10. Using the same procedure as before, collect force *vs.* time data.
11. Click or tap the graph to examine the data. The maximum value of the force occurs when the block started to slide. Click or tap the peak static friction force and record the value in your data table. **Note**: You can also adjust the Examine line by dragging the line.
12. Next you need to determine the average friction force while the block was moving at constant velocity.
    a. Select the data in the approximately constant-force region of the graph.
    b. Click or tap Graph Tools, , and choose View Statistics.
    c. Record the mean force value in your data table.
13. Repeat Steps 10–12 for two more measurements and average the results to determine the reliability of your measurements. Record the values in the data table. **Note**: The previous data set is automatically saved.
14. Add masses totaling 500 g to the block. Repeat Steps 10–13, recording values in the data table. Add another 500 g and repeat.

Part III Kinetic Friction Again

In this part, you will measure the coefficient of kinetic friction a second way and compare it to the measurement in Part II. Using the motion detector, you can measure the acceleration of the block as it slides to a stop. This acceleration can be determined from the velocity *vs.* time graph. While sliding, the only force acting on the block in the horizontal direction is that of friction. From the mass of the block and its acceleration, you can find the frictional force and finally, the coefficient of kinetic friction.

Figure 2

15. Place the motion detector on the lab table 1–2 m from a block of wood, as shown in Figure 2. Use the same surface you used in Part II. Position the motion detector so that it will detect the motion of the block as it slides toward the detector.

16. Set up the motion detector and Graphical Analysis.
    a. Disconnect the force sensor.
    b. Launch Graphical Analysis.
    c. Connect the Go Direct Motion Detector to your Chromebook or mobile device. Click or tap Sensor Channels.
    d. Select the check box for Motion (cart). Click or tap Done.
    e. If a position *vs*. time graph is displayed, click or tap the y-axis label and select only Velocity to display a graph of velocity *vs*. time.

17. Practice sliding the block toward the motion detector so that the block leaves your hand and slides to a stop. Minimize the rotation of the block. After it leaves your hand, the block should slide about 1 m before it stops and it must not come any closer to the motion detector than 0.25 m.

18. Collect data for the sliding block.
    a. Click or tap Collect to start data collection.
    b. After a moment, give the block a brief push so that it slides toward the motion detector.

19. Examine the graph of velocity *vs*. time. It should have a portion with a linearly decreasing section corresponding to the freely sliding motion of the block. Repeat data collection if needed.

20. Fit a straight line to this portion of the data, the slope of which is the block's acceleration.
    a. Select data in the region of linear decrease.
    b. Click or tap Graph Tools, , for the velocity *vs*. time graph and choose Apply Curve Fit.
    c. Select Linear as the curve fit and click Apply.
    d. Record the magnitude of the slope of the fitted line, which is the block's acceleration, in your data table.

21. Repeat Steps 18–20 two more times. **Note**: The previous data set is automatically stored.

22. Place masses totaling 500 g on the block. Fasten the masses so they will not separate from the block. Repeat Steps 18–20 three times for the block with masses. Record acceleration values in your data table.

DATA TABLE

Part I Starting Friction

Mass of block	kg

Part II Peak Static Friction and Kinetic Friction

Total mass (kg)	Normal force (N)	Peak static friction			Average peak static friction (N)
		Trial 1	Trial 2	Trial 3	

Total mass (kg)	Normal force (N)	Kinetic friction			Average kinetic friction (N)
		Trial 1	Trial 2	Trial 3	

Part III Kinetic Friction

Data: Block with no additional mass			
Trial	Acceleration (m/s^2)	Kinetic friction force (N)	μ_k
1			
2			
3			
Average coefficient of kinetic friction:			

Data: Block with 500 g additional mass			
Trial	Acceleration (m/s^2)	Kinetic friction force (N)	μ_k
1			
2			
3			
Average coefficient of kinetic friction:			

ANALYSIS

1. Inspect your force *vs.* time graph from Part I. Label the portion of the graph corresponding to the block at rest, the time when the block just started to move, and the time when the block was moving at constant speed.

2. Still using the force *vs.* time graph you created in Part I, compare the force necessary to keep the block sliding compared to the force necessary to start the slide. How does your answer compare to your answer to Preliminary Question 3?

3. The *coefficient of friction* is a constant that relates the normal force between two objects (blocks and table) and the force of friction. Based on your graph from Part I, would you expect the coefficient of static friction to be greater than, less than, or the same as the coefficient of kinetic friction?

4. For Part II, calculate the *normal force* of the table on the block alone and with each combination of added masses. Since the block is on a horizontal surface, the normal force will be equal in magnitude and opposite in direction to the weight of the block and any masses it carries. Fill in the Normal Force entries for both Part II data tables.

5. Plot a graph of the maximum (peak) static friction force (vertical axis) *vs.* the normal force (horizontal axis). Use Graphical Analysis or graph paper.

6. Since $F_{peak\ static} = \mu_s N$, the slope of this graph is the coefficient of static friction μ_s. Find the numeric value of the slope, including any units, by adding a Proportional Curve Fit. The Proportional Curve Fit passes through the origin.

7. In a similar graphical manner, find the coefficient of kinetic friction μ_k. Plot the average kinetic friction forces vs. the normal force. Recall that $F_{kinetic} = \mu_k N$ and the Proportional Curve Fit passes through the origin.

8. Your data from Part III will also allow you to determine μ_k. Draw a free-body diagram for the sliding block. The kinetic friction force can be determined from Newton's second law, or $\Sigma F = ma$. From the mass and acceleration, find the friction force for each trial, and enter it in the data table.

9. From the friction force, determine the coefficient of kinetic friction for each trial and enter the values in the data table. Also, calculate an average value for the coefficient of kinetic friction for the block and for the block with added mass.

10. Does the coefficient of kinetic friction depend on speed? Explain, using your experimental data.

11. Does the force of kinetic friction depend on the weight of the block? Explain.

12. Does the coefficient of kinetic friction depend on the weight of the block?

13. Compare your coefficients of kinetic friction determined in Part III to that determined in Part II. Discuss the values. Do you expect them to be the same or different?

EXTENSIONS

1. How does the surface area of the block affect the force of friction or the coefficient of friction? Devise an experiment that can test your hypothesis.

2. Examine the force of static friction for an object on an incline. Find the angle that causes a wooden block to start to slide. Calculate the coefficient of friction and compare it to the value you obtain when the angle of the incline is 0°.

3. Try changing the coefficient of friction by using wax or furniture polish on the table. How much does it change?

The Magnetic Field of a Permanent Magnet

A bar magnet is called a *dipole* because it has two poles (commonly labeled north and south). Breaking a magnet in two does not produce two isolated poles; each fragment still has two poles. Similarly, two magnets together still exhibit only two poles. Since, to our knowledge, there are no magnetic monopoles, the dipole is the simplest possible magnetic field source.

The dipole field is not limited to bar magnets, for an electrical current flowing in a loop also creates this common magnetic field pattern.

The magnetic field, B_{axis} (measured in tesla), of an ideal dipole measured along its axis is

$$B_{axis} = \frac{\mu_0}{4\pi} \frac{2\mu}{d^3}$$

where μ_0 is the permeability constant ($4\pi \times 10^{-7}$ T•m/A), d is the distance from the center of the dipole in meters and μ is the magnetic moment. The magnetic moment, μ, measures the strength of a magnet, much like electrical charge measures the strength of an electric field source. Note that the distance dependence of this function is an inverse-cube function, which is different from the inverse-square relationship you may have studied for other situations.

In this experiment, you will examine how the magnetic field of a small, powerful magnet varies with distance, measured along the axis of the magnet. A magnetic field sensor will be used to measure the magnitude of the field.

Simple laboratory magnets are approximately dipoles, although magnets of complex shapes will exhibit more complex fields. By comparing your field data to the field of an ideal dipole, you can see if your magnet is very nearly a dipole in its behavior. If it is nearly a dipole, you can also measure its magnetic moment.

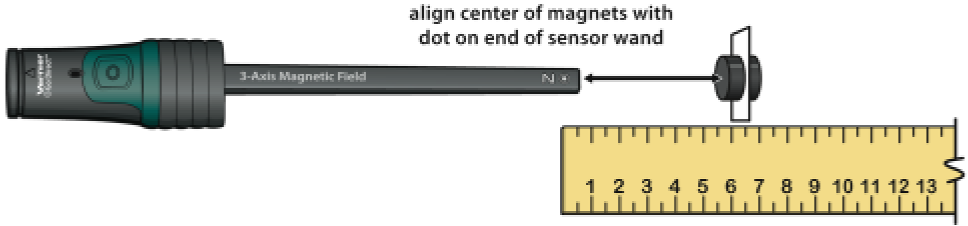

Figure 1

OBJECTIVES

- Measure the field of a small magnet.
- Compare the distance dependence of the magnetic field to the magnetic dipole model.
- Determine the magnetic moment of a magnet.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct 3-Axis Magnetic Field
masking tape
2 neodymium **or** ceramic magnets
tape measure **or** meter stick
index card

PRELIMINARY QUESTION

Place one magnet on a table and hold the other in your palm, well above the first. From directly above, slowly lower the upper magnet toward the first. Watch for the moment when the lower magnet jumps toward the back of your hand. Try it again. From the sudden jump of the lower magnet, what can you conclude about the way the magnetic force between the magnets varies with distance?

PROCEDURE

1. Launch Graphical Analysis. Connect the Go Direct 3-Axis Magnetic Field Sensor to your Chromebook, computer, or mobile device.

2. Set up the data-collection mode.

   a. Click or tap Mode to open Data Collection Settings. Change Mode to Event Based.

   b. Enter **Distance** as the Event Name and **m** as the Units. Click or tap Done.

3. Position the meter stick and the magnetic field sensor as shown in Figure 1. The body of the magnetic field sensor should be parallel to the meter stick, with the x-axis tip of the wand pointing in the direction of increasing distance. Identify the location of the sensor (marked with dots approximately 0.5 cm back from the tip) and align this location with the zero mark on your meter stick. When everything is in place, tape the sensor and meter stick to the table.

4. As a convenient way to measure to the center of the magnet, and to ease handling of the small magnets, allow the two magnets to attract one another through the card, about 0.5 cm from either edge near the corner. The magnets should stay in place on the card. The card will serve to mark the center of the magnet pair.

5. Zero the magnetic field sensor when the magnets are far away from the sensor in order to remove the effect of Earth’s magnetic field and any local magnetism. The magnetic field sensor will be zeroed only for this location. Instead of moving the sensor in later steps, you will move the magnet.

   a. Move the magnets at least 1 m from the sensor.

   b. Click or tap the X Magnetic Field meter and choose Zero.

6. Collect magnetic field data as a function of distance.

   a. Start data collection.

   b. Position the magnets so the card is perpendicular to the tip of the magnetic field sensor, 3 cm from the dots that mark the sensor's location (see Figure 1).

   c. Monitor the readings. If necessary, reverse the magnets so the magnetic field values are positive, and then reposition the magnets. If the reading is 5 mT, then increase the distance until the reading is below 5 mT.

   d. When the reading has stabilized, click or tap Keep.

   e. Enter the distance to the magnet. To make later calculations easier, enter the distance in meters (e.g., 3 cm is 0.03 m). Click or tap Keep Point to save this data pair.

7. Collect 10 additional data points.

   a. Taking care not to move the magnetic field sensor or meter stick, move the magnet 0.25 cm (0.0025 m) farther from the sensor.

   b. Click or tap Keep and enter the distance (in meters). Click or tap Keep Point.

   c. After the 11th point, stop data collection. The graph is the magnetic field *vs.* the distance from the magnet. The field should drop off rapidly.

DATA TABLE

Power regression parameter, *a*	
Power regression parameter, *b*	
Power regression equation	

Magnetic moment	
μ (A•m^2)	

ANALYSIS

1. A graph of magnetic field *vs.* distance is displayed. Is the data consistent with the equation for the magnetic field of a dipole described in the introduction?

   Compare your data to the inverse-cube model shown below using a power regression curve fit in Graphical Analysis

$$B_{axis} = \frac{\mu_0}{4\pi}\frac{2\mu}{d^3}$$

   a. Click or tap Graph Tools, , and choose Apply Curve Fit.

   b. Select Power as the curve fit and click or tap Apply.

c. A curve is fit to your data and parameters are shown on the graph. Record the parameter values in the data table and use them to write the power regression equation.

d. Export, download, or print the graph.

2. How well does the power regression fit your experimental data? An inverse cube function has b = 3. Does your data approximately follow an inverse cube function? From the comparison, does your magnet show the magnetic field pattern of a dipole?

3. Graphical Analysis adjusted *parameter a* so the equation's curve comes close to your data points. Relating the parameter a to the field expression for a magnetic dipole, we see that

$$a = \frac{\mu_0 2\mu (10^3)}{4\pi}$$

The factor of 10^3 is present because the magnetic field was measured in mT rather than T. Use your value of *a* to determine the magnetic moment μ of your magnet, if the power regression fits your experimental data.

EXTENSIONS

1. Find other magnets such as refrigerator magnets, horseshoe magnets, and cow magnets, and see if they also show the magnetic field of a dipole.

2. Measure the dipole moment of just one neodymium magnet, or four stuck together. Is the dipole moment additive when you use two or more magnets attracted together?

3. Show that the units of the magnetic moment are A•m^2 (ampere meter^2).

4. The units of μ may suggest a relationship of a magnetic moment to an electrical current. A current flowing in a closed loop is a magnetic dipole. A current, *I*, flowing around a loop of area πr^2 has a magnetic moment $\mu = I\, \pi r^2$. If a single current loop had the same radius as your permanent magnet, what current would be required to create the same magnetic field? (You will be surprised.) Are there currents flowing in loops in the permanent magnet?

Cart on a Ramp

(Sensor Cart)

This experiment uses an incline and a low-friction cart. If you give the cart a gentle push up the incline, the cart will roll upward, slow and stop, and then roll back down, speeding up. A graph of its velocity *vs.* time would show these changes. Is there a mathematical pattern to the changes in velocity? What is the accompanying pattern to the position *vs.* time graph? What does the acceleration *vs.* time graph look like? Is the acceleration constant?

In this experiment, you will use a Sensor Cart to collect position, velocity, and acceleration data for a cart rolling up and down an incline. Analysis of the graphs of this motion will answer the questions above.

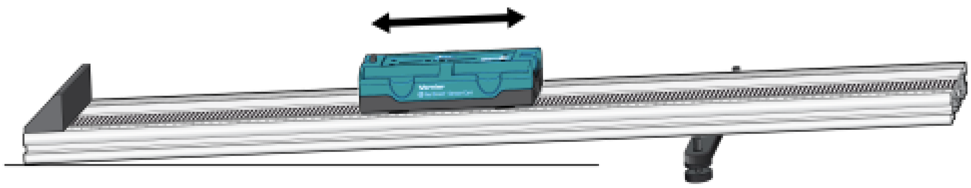

Figure 1

OBJECTIVES

- Collect position, velocity, and acceleration data as a cart rolls freely up and down an incline.
- Analyze position *vs.* time, velocity *vs.* time, and acceleration *vs.* time graphs.
- Determine the best fit equations for the position *vs.* time and velocity *vs.* time graphs.
- Determine the mean acceleration from the acceleration *vs.* time graph.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Sensor Cart
Vernier Dynamics Track
Adjustable End Stop

PRELIMINARY QUESTIONS

1. Consider the changes in motion that a cart will undergo as it rolls up and down an incline. Make a sketch of your prediction for the position *vs.* time graph. Describe in words what this graph means.
2. Make a sketch of your prediction for the velocity *vs.* time graph. Describe in words what this graph means.
3. Make a sketch of your prediction for the acceleration *vs.* time graph. Describe in words what this graph means.

PROCEDURE

Part I

1. Launch Graphical Analysis. Connect the Sensor Cart to your Chromebook, computer, or mobile device.

2. Place the cart on the track near the Adjustable End Stop. Point the **+x** arrow toward the top of the ramp. Click or tap Collect to start data collection. Wait about a second, then briefly push the cart up the incline, letting it roll freely up nearly to the top, and then back down. Catch the cart as it nears the end stop.

3. Examine the position *vs.* time graph. Repeat Step 2 if your position *vs.* time graph does not show an area of smoothly changing position. Check with your instructor if you are not sure whether you need to repeat data collection.

4. Answer the Analysis questions for Part I before proceeding to Part II.

Part II

5. Your cart can bounce against the end stop with its plunger. Practice starting the cart so it bounces at least twice during data collection.

6. Collect another set of data showing two or more bounces. **Note**: The previous data set is automatically saved.

7. Proceed to the Analysis questions for Part II.

ANALYSIS

Part I

1. Export, print, or sketch the three motion graphs. To view the acceleration *vs.* time graph, change the y-axis of either graph to Acceleration. The graphs you have recorded are fairly complex and it is important to identify different regions of each graph. Record your answers directly on the printed or sketched graphs.

   a. Identify the region when the cart was being pushed by your hand:

      - Examine the velocity *vs.* time graph and identify the region. Label it on the graph.
      - Examine the acceleration *vs.* time graph and identify the same region. Label the graph.

   b. Identify the region where the cart was rolling freely:

      - Label the region on each graph where the cart was rolling freely and moving up the incline.
      - Label the region on each graph where the cart was rolling freely and moving down the incline.

c. Determine the position, velocity, and acceleration at specific points:

- On the velocity *vs.* time graph, decide where the cart had its maximum velocity, just as the cart was released. Mark the spot and record the value on the graph.
- On the position *vs.* time graph, locate the highest point of the cart on the incline. Mark the spot and record the value on the graph.
- What was the velocity of the cart at the top of its motion?
- What was the acceleration of the cart at the top of its motion?

2. The motion of an object in constant acceleration is modeled by the equation $x = \frac{1}{2} at^2 + v_0 t + x_0$, where x is the position, a is the acceleration, t is time, and v_0 is the initial velocity. This is a quadratic equation whose graph is a parabola. If the cart moved with constant acceleration while it was rolling, your graph of position *vs.* time will be parabolic.

   a. Select the data in the parabolic region of the position graph.
   b. Click or tap Graph Tools, , for the position *vs.* time graph and choose Apply Curve Fit.
   c. Select Quadratic as the curve fit and click or tap Apply.
   d. Record the parameters of the fitted curve (the acceleration).

   Is the cart's acceleration constant during the free-rolling segment?

3. The graph of velocity *vs.* time is linear if the acceleration is constant. Fit a line to the data.

   a. Select the data in the linear region of the velocity graph.
   b. Click or tap Graph Tools, , for the velocity *vs.* time graph and choose Apply Curve Fit.
   c. Select Linear as the curve fit and click or tap Apply.
   d. Record the slope of the fitted line (the acceleration).

   How closely does the slope correspond to the acceleration you found in the previous step?

4. Change the y-axis to Acceleration. The graph of acceleration *vs.* time should appear approximately constant during the freely-rolling segment.

   a. Select the data in the region of the graph that represents when the cart was rolling freely.
   b. Click or tap Graph Tools, , for the acceleration *vs.* time graph and choose View Statistics.

   How closely does the mean acceleration compare to the values of acceleration found in Steps 2 and 3?

Part II

1. Determine the cart's acceleration during the free-rolling segments using the velocity graph. Are they the same?

2. Determine the cart's acceleration during the free-rolling segments using the position graph. Are they the same?

EXTENSIONS

1. Use a free-body diagram to analyze the forces on a rolling cart. Predict the acceleration as a function of incline angle and compare your prediction to your experimental results. For a trigonometric method for determining θ, see the experiment, "Determining g on an Incline," in this book.

2. Even though the cart has very low friction, the friction is not zero. From your velocity graph, devise a way to measure the difference in acceleration between the roll up and the roll down. Can you use this information to determine the friction force in newtons?

Impulse and Momentum

(Sensor Cart)

The impulse-momentum theorem relates impulse, the average force applied to an object times the length of time the force is applied, and the change in momentum of the object:

$$\overline{F}\Delta t = mv_f - mv_i$$

Here, we will only consider motion and forces along a single line. The average force, $\overline{F}$, is the average *net* force on the object, but in the case where one force dominates and other forces are negligible, it is sufficient to use only the large force in calculations and analysis.

For this experiment, a Sensor Cart equipped with a hoop string will roll along a level track. Its momentum will change as it collides with the end stop at the end of the track. The hoop will compress and apply an increasing force until the cart stops. The cart then changes direction and the hoop expands back to its original shape. The force applied by the spring and cart velocity throughout the motion are measured by the Sensor Cart. You will then use data-collection software to determine the impulse in order to test the impulse-momentum theorem.

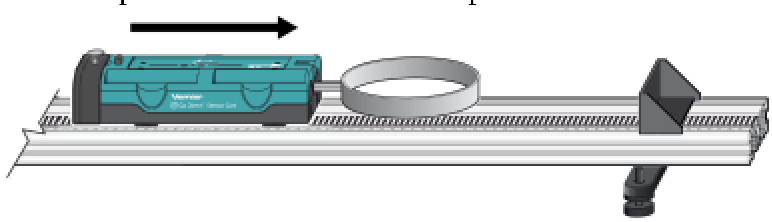

Figure 1

OBJECTIVES

- Measure a cart’s momentum change and compare it to the impulse it receives.
- Compare average and peak forces in impulses.

MATERIALS

Chromebook, computer, **or** mobile device
Graphical Analysis 4 app
Go Direct Sensor Cart
Vernier Dynamics Track
Accessories from the Bumper and Launcher Kit: Hoop Bumper, clay, and clay holder

PRELIMINARY QUESTIONS

1. In a car collision, the driver’s body must change speed from a high value to zero. This is true whether or not an airbag is used, so why use an airbag? How does it reduce injuries?

2. Two playground balls, the type used in the game of dodgeball, are inflated to different levels. One is fully inflated and the other is flat. Which one would you rather be hit with? Why?

PROCEDURE

1. Attach the hoop spring to the cart. Measure the mass of the cart and record the value in the data table.

2. Attach the End Stop to the end of the track as shown in Figure 1.

3. Place the track on a level surface. Confirm that the track is level by placing the cart on the track and releasing it from rest. It should not roll. If necessary, adjust the track to level it.

4. Set up the sensor and data-collection software.

   a. Launch Graphical Analysis.
   b. Connect the Go Direct Sensor Cart to your Chromebook, computer, or mobile device.
   c. Click or tap Sensor Channels.
   d. Enable the Force channel in addition to the Position channel. Click or tap Done.

5. Zero the Force channel.

   a. Remove all force from the hoop spring.
   b. Click or tap the Force meter and choose Zero.

6. Set up the data-collection mode.

   a. Click or tap Mode to open data-collection settings.
   b. Change the Rate to 250 samples/s and End Collection to 5 s. Click or tap Done.

Part I Elastic collisions

7. Practice releasing the cart so it rolls toward the end stop, bounces gently, and returns to your hand. The cart must stay on the track.

8. Position the cart so that the cart is approximately 50 cm from the end stop. Click or tap Collect to start data collection, then roll the cart as you practiced in the previous step.

9. Study your graphs to determine if the run was useful. Confirm that you can see a region of constant velocity before and after the impact. If necessary, repeat data collection.

10. Once you have made a run with good position, velocity, and force graphs, analyze your data. To test the impulse-momentum theorem, you need the velocity before and after the impulse. To find these values, work with the graph of velocity *vs.* time.

    a. On the Velocity graph, select an interval corresponding to a time before the impulse, when the cart was moving at approximately constant speed toward the end stop.
    b. Click or tap Graph Tools, , and choose View Statistics. Read the average velocity before the collision (v_i) and record the value in the data table.
    c. Dismiss the Statistics box.
    d. Repeat parts a–c of this step to determine the average velocity just after the impulse, when the cart was moving at approximately constant speed away from the end stop. Record this value in the data table.

11. Now you will calculate the value of the impulse. Use the first method if you have studied calculus and the second if you have not.

    Method 1 Calculus version

    Calculus tells us that the expression for the impulse is equivalent to the integral of the force *vs.* time graph, or

$$\bar{F}\Delta t = \int_{t_{initial}}^{t_{final}} F(t)dt$$

    Calculate the integral of the impulse on your force *vs.* time graph.

    a. Select the region that represents the impulse (begin at the point where the force becomes non-zero).
    b. Click or tap graph tools, , and choose View Integral.
    c. Read the value of the integral of the force data, the impulse value, and record the value in the data table.

    Method 2 Non-calculus version

    Calculate the impulse from the average force on your force *vs.* time graph. The impulse is the product of the average (mean) force and the length of time that force was applied, or $\bar{F}\Delta t$.

    a. Select the region that represents the impulse (begin at the point where the force becomes non-zero).
    b. Click or tap Graph Tools, , and choose View Statistics.
    c. Record the average (mean) force value in the data table.
    d. Since time is on the horizontal axis of the graph, the Δx provided in the statistics is the Δt for the selected region. Record this value as Δt in your data table.
    e. From the average force and time interval, determine the impulse, $\bar{F}\Delta t$, and record this value in your data table.

12. Repeat Steps 8–11 two more times to collect a total of three trials; record the information in your data table.

Part II Inelastic collisions

13. Replace the hoop spring bumper with one of the clay holders from the Bumper and Launcher Kit. Attach cone-shaped pieces of clay to both the clay holder and to the end stop, as shown in Figure 2. Measure the mass of the cart and record the value in the data table.

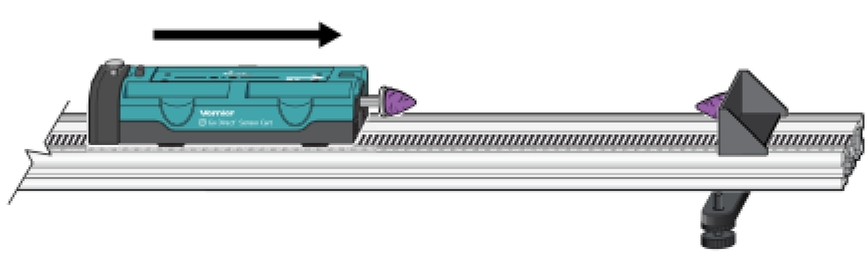

Figure 2

14. Place the cart on the track as shown in Figure 2. Click or tap the Force meter and choose Zero to zero the Force Sensor.

15. Practice launching the cart so that when the clay on the front of the cart collides with the clay on the end stop, the cart comes to a stop without bouncing.

16. Position the cart so that the cart is approximately 50 cm from the end stop. Click or tap Collect to start data collection, then roll the cart so that the clay pieces collide and stick together.

17. Study your graphs to determine if the run was useful. Confirm that you can see a region of constant velocity before and after the impact. If necessary, reshape the clay pieces and repeat data collection.

18. Once you have made a run with good position, velocity, and force graphs, analyze your data. To test the impulse-momentum theorem, you need the velocity before and after the impulse.

    a. On the Velocity graph, select the interval corresponding to the time before the impact. Click or tap Graph Tools, , and choose View Statistics. Record the average velocity in the data table.

    b. Dismiss the Statistics box.

    c. Select the interval corresponding to the time after the impact. Then, click or tap Graph Tools, , and choose View Statistics. Record the average velocity in the data table.

    d. Dismiss the Statistics box.

19. Now you will calculate the value of the impulse. Similar to Step 11, use the first method if you have studied calculus and the second if you have not.

    Method 1 Calculus version

    Calculate the integral of the impulse on your force *vs.* time graph.

    a. Select the impulse, then click or tap graph Tools, , and choose View Integral.

    b. Record the impulse value in the data table.

    Method 2 Non-calculus version

    Calculate the impulse from the average force on your force *vs.* time graph.

    a. Select the impulse. Click or tap Graph Tools, , and choose View Statistics. Record the average force in the data table.

    b. Since time is on the horizontal axis of the graph, the Δx provided in the statistics is the Δt for the selected region. Record this value as Δt in your data table.

    c. From the average force and time interval, determine the impulse, $\bar{F}\Delta t$, and record this value in your data table.

20. Repeat Steps 16–19 two more times to collect a total of three trials; record the information in your data table. **Note**: You will need to reshape the clay pieces before each trial.

DATA TABLE

Mass of cart (elastic collision)	kg
Mass of cart (inelastic collision)	kg

Method 1 Calculus version						
Trial	Final velocity v_f (m/s)	Initial velocity v_i (m/s)	Change of velocity Δv (m/s)	Impulse (N•s)	Change in momentum (kg•m /s) or (N•s)	% difference between Impulse and Change in momentum
Elastic 1						
2						
3						
Inelastic 1						
2						
3						

Method 2 Non-calculus version								
Trial	Final velocity v_f (m/s)	Initial velocity v_i (m/s)	Change of velocity Δv (m/s)	Average force $\bar{F}$ (N)	Duration of impulse Δt (s)	Impulse $\bar{F}\Delta t$ (N•s)	Change in momentum (kg•m /s) or (N•s)	% difference between Impulse and Change in momentum
Elastic 1								
2								
3								
Inelastic 1								
2								
3								

ANALYSIS

1. Calculate the change in velocities and record the result in the data table. From the mass of the cart and the change in velocity, determine the change in momentum that results from the impulse. Make this calculation for each trial and enter the values in the data table.

2. If the impulse-momentum theorem is correct, the change in momentum will equal the impulse for each trial. Experimental measurement errors, along with friction and shifting of the track, will keep the two from being exactly the same. One way to compare the two is to find their percentage difference. Divide the difference between the two values by the average of the two, then multiply by 100%. How close are your values, percentage-wise? Do your data support the impulse-momentum theorem?

3. Look at the shape of the last force *vs.* time graph. Is the peak value of the force significantly different from the average force? Is there a way you could deliver the same impulse with a much smaller force?

4. Revisit your answers to the Preliminary Questions in light of your work with the impulse-momentum theorem.