# Lab 7. Newton's Third Law and Momentum

## Goals

- To explore the behavior of forces acting between two objects when they touch one another or interact with one another by some other means, such as a light string.
- To compare the magnitudes of the forces exerted by one object on another object and vice versa during collisions.
- To experimentally explore the relationship between an impulse and a change in motion.
- To understand the relationship between impulse and momentum.
- To explore and understand conservation of momentum.

## Introduction

You have already explored how the motion of an object is affected by applied forces, such as gravity. We have not dealt with the idea of what force interactions really are.

The important note made by Newton's Third Law is that forces are not properties of individual objects. What right now is the force of your left hand? What was the force of your body yesterday?

Neither of these questions make enough sense to answer. However, I could ask what force your hand is applying to a book which you are holding up. I could ask what was the force of your body on a chair when sitting down yesterday.

The important change is that I have now asked for a force that is 1) doing something, and 2) involving two objects. Forces are interactions between two objects. There is one force shared by the two objects, and the force is either attractive (direction of force on each objects points toward the other object), or repulsive (direction of force on each object points away from the other object).

Many approaches to Newton's Third Law talk about Force Pairs. Questions testing if you understand Newton's Third Law ask things like "If a motorcycle and an 18-wheeler collide, which one exerts the larger force?" These questions and the idea of pairing forces for "equal and opposite reaction force" can lead to much confusion, as it invites the idea that forces are properties of single objects, and that by some coincidence or mechanism there will be a possibility to find two matched forces.

This is a faulty approach to Newton's Third law. Forces are interactions, there is one force which is acting between two objects. You can consider the effects of the force on each object individually, which is what leads to the idea of "How much force did the Motorcycle apply to the 18-wheeler?" but this choice is one we are making in order to calculate vectors, since the direction of the force on each of the two objects are opposite to one another.

In this experiment we focus on forces acting between two smaller objects.

We also wish to explore the relationship between the impulse, defined as the area under the force-versus-time graph during a brief interaction, to changes in the momentum, $mv$, of an object with mass $m$ and velocity $v$. Finally we will look at the momentum of a two-body system of masses immediately before and after they interact with each other.

# Forces of interaction—Connected objects

Two force sensors are attached individually to the tops of two carts that can roll on an aluminum track. Before beginning any measurements, make sure that both force sensors are "zeroed" by pressing the "tare" button on the side of each sensor while there is nothing pushing or pulling on the hook of that sensor. Check by means of a quick force-time graph that both sensors really read very close to zero. Also make certain that the data sampling rate that you have set is sufficiently high to record the force variations that take place. If the graphs look "jagged," with straight line segments connecting the data points, then increase the sampling rate until the lines connecting the data points form a smooth curve (even when you expand the time scale). Notice that if you read the supposedly zero force for a longer period of time, it drifts away from zero. To avoid complications from this "zero drift" you will zero your sensors before each data collection today.

Note that the force sensor mounted on Cart 1 measures the force exerted on Cart 1 by Cart 2, and the force sensor mounted on Cart 2 measures the force exerted on Cart 2 by Cart 1. Since the force sensors are oriented "back-to-back," one sensor will measure positive forces to the right and the other will measure positive forces to the left. This difference is critical because forces are vector quantities. It is possible to change the settings to reverse the readings of one sensor so that both forces measure as positive when the carts are pulling apart, and negative when they are pushing together.

## Carts with equal masses

Place both carts on the track and connect the hooks on the force sensors together using the twisted copper wire. Place one hand on each cart (you can use both hands or work with your lab partner) and push them together or pull them apart (not excessively; getting too violent here can damage the force sensors!) all the while recording both forces as a function of time. Sketch a representative time segment of your data in your lab notes. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? Do your conclusions change if the carts experience a nonzero acceleration? What can you conclude about the direction of the force on each cart due to the other cart? Remember to zero (tare) the force sensors before each set of measurements!

### Carts with unequal masses

Add two steel bars (approximately 0.5 kg each) to the cart on the right. With your hand touching only the cart on the left, pull and push the cart on the right while recording a graph displaying both forces as a function of time. (Of course the force sensor hooks must still be connected.) From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? Do your conclusions change if the carts experience a nonzero acceleration? What can you conclude about the direction of the force on each cart due to the other cart?

### Carts connected by string

Now connect the carts with a short length of string. (Only "pulls" are possible with a string, because the string goes slack if you push the carts together.) Do your conclusions change if the carts experience a nonzero acceleration? How does the presence of the string between the carts affect your answers regarding the forces you observed previously?

### Summary of forces of interaction—connected objects

Summarize your conclusions for connected objects clearly and concisely before continuing. Compare your results with what you would predict on the basis of Newton's Third Law. Several common mistakes in homework and on exams relate to the observations you have just made. Ask your teaching assistant if you have any doubts.

## Force of interaction—Colliding objects

### "Bouncy" collisions with equal cart masses

Mount the springs in place of the hooks on the ends of the force sensors. When screwing the springs on, you are not screwing them in until they cannot screw any further, you are just getting them to grip enough that you are unable to pull the springs out with a light tug.

Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Don't push the cart so hard that the springs totally compress during the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision and rescale the graph to show this region clearly. You may also need to adjust the sampling rate of the force sensors to get sufficient data during the collision itself. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## "Bouncy" collisions with unequal cart masses

Add two steel bars (approximately 1 kg) to one of the carts. Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Perform two trials, first with the high-mass cart stationary and second with the low-mass cart stationary. Again avoid pushing the cart so hard that the springs totally compress during the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision and rescale the graph to show this region clearly. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## 'Sticky" collisions with equal cart masses

Remove the springs from the ends of the force sensors and replace them with small metal "cups" holding pieces of clay. Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Disregard any trial in which the carts don't remain stuck together after the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision and rescale the graph to show this region clearly. You may also need to adjust the sampling rate of the force sensors to get sufficient data during the collision itself. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## "Sticky" collisions with unequal cart masses

Add two steel bars (approximately 1 kg) to one of the carts. Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Perform two trials, first with the high-mass cart stationary and second with the low-mass stationary. Disregard any trial in which the carts don't remain stuck together after the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision. Rescale the graph to show this region clearly. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer

answer (both carts moving in the same direction compared against both carts moving toward each other)

### Summary for forces of interaction—colliding objects

Summarize your conclusions for "bouncy" and "sticky" collisions clearly and concisely before proceeding. Based on your observations how are the results changed by the different collision conditions? You will eventually learn that mechanical energy is lost in sticky collisions but is mostly conserved in bouncy collisions. Something that is true in both kinds of collisions can help you when the concept of conservation of energy is not useful.

## Impulse and momentum during collisions

In this experiment, you will measure the impulse delivered to a cart as it strikes the end of the track. The bracket mounted at one end of the Pasco track has a small hole at just the right height for mounting a spring or clay cup to meet the end of the force sensor on the cart. The impulse is calculated by finding the "area" under the force-time curve during the collision using Capstone. This area has the units of force $\times$ time, or N-s. The impulse will be compared to the change in momentum of your cart. Momentum has units of kg-m/s. Show that units of N-s are equivalent to momentum units in your notes.

The change in momentum experienced by the cart can be calculated from the velocities of the cart just before and after the collision. An ultrasonic motion sensor is used to measure the velocity of the cart. Please refer to the Computer Tools Supplement at the end of your lab manual for more information on using the motion sensor.

### Impulse and momentum in "sticky" collisions

Screw the clay cup from the unused force sensor into the bracket at the end of the track, and set up the motion sensor to measure the velocity of the cart as it moves down the track. The force sensor on the cart you are using should still have the clay cup attached to it. Give the cart a quick push down the leveled track so that it sticks to the clay on the end bracket. Disregard any trial when it doesn't stick securely. Display graphs of the force and the velocity as functions of time as the cart travels down the track and sticks to the end.

To find the impulse (the area under the force-time plot), use the "Highlight range of points in active data" tool (icon with yellow pencil and red points) along the top of the graph to select the force data that correspond to the collision. Then click on the "Display area under active data" icon (red line shaded below in gray). The area under the selected force data will appear in a box on the graph in units of N-s. Now compare the values of the impulse of the contact force during the collision with the change in momentum of the cart. What conclusion can you draw from your data? Several trials may be necessary to discover a pattern. Remember that impulse and momentum are vector quantities, so the positive $x$-directions for the force sensor and the motion sensor need to be considered carefully.

### Impulse and momentum in "bouncy" collisions

Replace the clay cups with the springs to produce a bouncy collision at the end of the track. Again compare the values of the impulse of the contact force during the collision with the change in momentum of the cart. What conclusion can you draw from your data? Several trials may be necessary.

### Summary for impulse and momentum in collisions

Summarize your conclusions for "sticky" and "bouncy" collisions clearly and concisely before proceeding. Based on your observations, how do the results compare when the collision conditions change?

## Conservation of momentum

Using the motion sensor with clay cups on both carts, explore whether the sum of the momenta of the two carts is the same before and after a "sticky" collision. We investigate only the "sticky" collision, because we can determine the total momentum with only one velocity measurement before the collision and one after. That is all the motion sensor can do.

### Equal cart masses

Push the cart closest to the motion sensor toward the second stationary cart so the carts stick together and move off together after the collision. Compare the momentum of the system of the two carts just prior to the collision with the combined momentum just after the collision. Several trials may be necessary to get a good measurement of the velocity after collision, where the carts stick together.

### Unequal cart masses

Add two steel bars to the cart closest to the motion sensor and repeat the experiment. Compare once again the momentum of the two-cart system before and after the collision. Several trials are in order.

### Summary for conservation of momentum

Summarize your conclusions for equal and unequal cart masses clearly and concisely before going to the Synthesis section. Based on your observations, how are the results changed by varying the cart masses? What predictions can be made regarding the total momentum of both carts just prior to a collision compared to the total momentum of both carts just after the collision? Do your experimental momentum measurements results agree with your predictions about the momentum of the two-cart system before and after the collision?

## Synthesis

Using your observations on forces between interacting objects, discuss how the impulses given to the carts in a two-cart collision are (should be) related. (Refer to Newton's Third Law.) From your observations of impulse and momentum, how do the momenta of the two carts change during a collision if the contact forces during the collision represent for all practical purposes the net forces acting on the carts? Remember that the change in any quantity is defined as the final value minus the initial value. Impulse and momentum are vector quantities, so you need to pay close attention to directions as well as magnitudes.

## Grading Rubric

| | No Effort | Progressing | Expectation | Exemplary |
|---|---|---|---|---|
| **AA** Is able to extract the information from representation correctly Labs: 1-12 | No visible attempt is made to extract information from the experimental setup. | Information that is extracted contains errors such as labeling quantities incorrectly, mixing up initial and final states, choosing a wrong system, etc. Physical quantities have no subscripts (when those are needed). | Most of the information is extracted correctly, but not all of the information. For example physical quantities are represented with numbers and there are no units. Or directions are missing. Subscripts for physical quantities are either missing or inconsistent. | All necessary information has been extracted correctly, and written in a comprehensible way. Objects, systems, physical quantities, initial and final states, etc. are identified correctly and units are correct. Physical quantities have consistent and informative subscripts. |
| **AB** Is able to construct new representations from previous representations Labs: 1-12 | No attempt is made to construct a different representation. | Representations are attempted, but omits or uses incorrect information (i.e. labels, variables) or the representation does not agree with the information used. | Representations are constructed with all given (or understood) information and contain no major flaws. | Representations are constructed with all given (or understood) information and offer deeper insight due to choices made in how to represent the information. |
| **AC** Is able to evaluate the consistency of different representations and modify them when necessary Labs: 2-10, 12 | No representation is made to evaluate the consistency. | At least one representation is made but there are major discrepancies between the constructed representation and the given experimental setup. There is no attempt to explain consistency. | Representations created agree with each other but may have slight discrepancies with the given experimental representation. Or there is inadequate explanation of the consistency. | All representations, both created and given, are in agreement with each other and the explanations of the consistency are provided. |

| | No Effort | Progressing | Expectation | Exemplary |
|---|---|---|---|---|
| **AE**<br>Force Diagram<br>Labs: 1-12 | No representation is constructed. | Force Diagram is constructed but contains major errors such as mislabeled or not labeled force vectors, length of vectors, wrong direction, extra incorrect vectors are added, or vectors are missing. | Force Diagram contains no errors in vectors but lacks a key feature such as labels of forces with two subscripts vectors are not drawn from single point, or axes are missing. | The diagram contains no errors and each force is labeled so that it is clearly understood what each force represents. Vectors are scaled precisely. |
| **AF**<br>Sketch<br>Labs: 1, 4, 5, 7-9, 11, 12 | No representation is constructed. | Sketch is drawn but it is incomplete with no physical quantities labeled, or important information is missing, or it contains wrong information, or coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities. Subscripts are missing or inconsistent. Majority of key items are drawn. | Sketch contains all key items with correct labeling of all physical quantities have consistent subscripts; axes are drawn and labeled correctly. |
| **AG**<br>Mathematical<br>Labs: 2-5, 7-12 | No representation is constructed. | Mathematical representation lacks the algebraic part (the student plugged the numbers right away) has the wrong concepts being applied, signs are incorrect, or progression is unclear. | No error is found in the reasoning, however they may not have fully completed steps to solve problem or one needs effort to comprehend the progression. | Mathematical representation contains no errors and it is easy to see progression of the first step to the last step in solving the equation. The solver evaluated the mathematical representation with comparison to physical reality. |
| **AI**<br>Graph<br>Labs: 1, 2, 4-8, 10-12 | No graph is present. | A graph is present but the axes are not labeled. There is no scale on the axes. The data points are connected. | The graph is present and axes are labeled but the axes do not correspond to the independent and dependent variable or the scale is not accurate. The data points are not connected but there is no trend-line. | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |
| **CA**<br>Is able to identify the hypothesis to be tested<br>Labs: 4, 5, 7-9, 12 | No mention is made of a hypothesis. | An attempt is made to identify the hypothesis to be tested but is described in a confusing manner. | The hypothesis to be tested is described but there are minor omissions or vague details. | The hypothesis is clearly stated. |

| | No Effort | Progressing | Expectation | Exemplary |
|---|---|---|---|---|
| **CC**<br>Is able to make a reasonable prediction based on a hypothesis<br>Labs: 4, 5, 7-9, 12 | No prediction is made. The experiment is not treated as a testing experiment. | • A prediction is made but it is identical to the hypothesis OR<br>• Prediction is made based on a source unrelated to hypothesis being tested OR<br>• is completely inconsistent with hypothesis being tested OR<br>• Prediction is unrelated to the context of the designed experiment. | Prediction follows from hypothesis but is flawed because<br>• relevant experimental assumptions are not considered and/or<br>• prediction is incomplete or somewhat inconsistent with hypothesis and/or<br>• prediction is somewhat inconsistent with the experiment. | A prediction is made that<br>• follows from hypothesis,<br>• is distinct from the hypothesis,<br>• accurately describes the expected outcome of the designed experiment,<br>• incorporates relevant assumptions if needed. |
| **CD**<br>Is able to identify the assumptions made in making the prediction<br>Labs: 4, 5, 7-9, 12 | No attempt is made to identify any assumptions. | An attempt is made to identify assumptions, but the assumptions are irrelevant or are confused with the hypothesis. | Relevant assumptions are identified but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |
| **CE**<br>Is able to determine specifically the way in which assumptions might affect the prediction<br>Labs: 4, 5, 7-9, 12 | No attempt is made to determine the effects of assumptions. | The effects of assumptions are mentioned but are described vaguely. | The effects of assumptions are determined, but no attempt is made to validate them. | The effects of the assumptions are determined and the assumptions are validated. |
| **CF**<br>Is able to decide whether the prediction and the outcome agree/disagree<br>Labs: 4, 5, 7-9, 124, 5, 7-9, 12 | No mention of whether the prediction and outcome agree/disagree. | A decision about the agreement/disagreement is made but is not consistent with the outcome of the experiment. | A reasonable decision about the agreement/disagreement is made but experimental uncertainty is not properly taken into account. | A reasonable decision about the agreement/disagreement is made and experimental uncertainty is taken into account. |
| **CG**<br>Is able to make a reasonable judgment about the hypothesis<br>Labs: 4, 5, 7-9, 12 | No judgment is made about the hypothesis. | A judgment is made but is not consistent with the outcome of the experiment. | A judgment is made, is consistent with the outcome of the experiment, but assumptions are not taken into account. | A judgment is made, consistent with the experimental outcome, and assumptions are taken into account. |

| | No Effort | Progressing | Expectation | Exemplary |
|---|---|---|---|---|
| **GD**<br>Is able to record and represent data in a meaningful way<br>Labs: 1-12 | Data are either absent or incomprehensible. | Some important data are absent or incomprehensible. They are not organized in tables or the tables are not labeled properly. | All important data are present, but recorded in a way that requires some effort to comprehend. The tables are labeled but labels are confusing. | All important data are present, organized, and recorded clearly. The tables are labeled and placed in a logical order. |
| **GE**<br>Is able to analyze data appropriately<br>Labs: 1-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed or inappropriate. | The analysis is appropriate but it contains minor errors or omissions. | The analysis is appropriate, complete, and correct. |
| **IA**<br>Is able to conduct a unit analysis to test the self-consistency of an equation<br>Labs: 1-12 | No meaningful attempt is made to identify the units of each quantity in an equation. | An attempt is made to identify the units of each quantity, but the student does not compare the units of each term to test for self-consistency of the equation. | An attempt is made to check the units of each term in the equation, but the student either mis-remembered a quantity's unit, and/or made an algebraic error in the analysis. | The student correctly conducts a unit analysis to test the self-consistency of the equation. |

**EXIT TICKET:**

- ☐ Put the hooks back on the force sensors.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Report any problems or suggest improvements to your TA.
- ☐ Have TA validate Exit Ticket Complete.